# A

## 'AIN GHAZAL

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### Definition

'Ain Ghazal ("Spring of the Gazelles") is a major Neolithic settlement located near Amman in northwestern Jordan. The site is situated on footslopes and toeslopes in the Zarqa River valley, the second largest tributary of the Jordan River. Archaeological excavations were conducted at 'Ain Ghazal during seasons beginning in 1982. Although a relatively small portion of the site has been excavated, the findings have been remarkable and have brought about the reevaluation of some basic assumptions regarding Neolithic life (Simmons, 2007). The most significant discoveries at the site relate to chronology, size and population, economy, ritual and artistic life, ecological adaptation, and the ultimate abandonment of the site.

Covering an area of at least 12 ha, 'Ain Ghazal is three times the size of Jericho and represents one of the largest aceramic Neolithic sites recorded in the Near East. Hence, it probably was a major population center, although the entire site may not have been occupied at the same time. At its peak, 'Ain Ghazal probably had a population of several thousand people, but after 8,500 cal years BP, the population dropped sharply.

Based on a large suite of radiocarbon ages, a major occupation occurred at 'Ain Ghazal between ca. 10,200 and 8,000 cal years BP, which corresponds to the Pre-Pottery Neolithic B (PPNB) (Simmons et al., 1988). There also was an occupation during the succeeding Pre-Pottery Neolithic C, and the site continued to be occupied into the Pottery Neolithic component, locally known as the Yarmoukian (Rollefson, 1993). The Yarmoukian component at 'Ain Ghazal dates to ca. 7,700 cal years BP (Kafafi et al., 2012: 27). In addition, Chalcolithic pastoralists appear to have occupied the site during two brief intervals around 7,200 and 6,500 cal years BP (Zielhofer et al., 2012). Aceramic and ceramic components often occur at major Neolithic sites, but they are often separated by a hiatus in the period of occupation. This is not the case at 'Ain Ghazal; a transitional phase from aceramic to ceramic was documented, the aforementioned Pre-Pottery Neolithic C (PPNC) (Simmons et al., 1988). The PPNC component shares elements common to both the PPNB and Yarmoukian, yet it is unique in many ways.

The recovery of abundant faunal and floral remains at 'Ain Ghazal provided a wealth of information about subsistence strategies during the periods of occupation. Goats dominate the faunal assemblage and, along with cattle, were used in a domestic sense (Köhler-Rollefson et al., 1988), although they may not have been morphologically domestic (Simmons et al., 1988). Also, a remarkable variety of wild animals were consumed at the site during the PPNB, with over 50 taxa identified in the assemblage, although by the second half of the 8th millennium, the wild component drops dramatically (von den Driesch and Wodtke, 1997). Gazelle, pig, hare, fox, and turtles are especially abundant. Plant foods appear to be dominated by legumes (primarily peas and lentils), though wheat, barley, chickpea, fig, and a wide variety of wild plants also were consumed (Donaldson, 1984; Neef, 2004).

'Ain Ghazal contains remarkably sophisticated and well-preserved architecture. During the Middle PPNB, housing consisted mostly of two-roomed rectangular dwellings with walls made of stones set in mud mortar. The interior faces of the structures were covered with

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mud plaster and coated with a thin layer of fine plaster, often decorated with red ochre. Floors were made of a high-quality plaster burnished to a high gloss and usually painted with red ochre. Sunken plastered hearths occur in the main living quarters, and often second rooms appear to have functioned as storage and food-processing areas. Wooden posts ran up some of the walls and from central portions of the floors to support the roof.

The most spectacular discovery at the site was two caches of human statues and busts in the Middle PPNB levels. The statues are 80–100 cm tall and consist of high-quality white plaster around a core of bundled reeds; the busts also are made of plaster. In all, 32 plaster figures were recovered, 15 full figures, 15 busts, and two fragmentary heads. The statues have painted clothes, hair, and, in some cases, ornamental tattoos or body paint. The alignment of the statues in two tiers and the arrangement of the busts in an arc at the feet of the statues point to ritual behavior at 'Ain Ghazal.

Additional ritual behavior at 'Ain Ghazal is evidenced by smaller clay figures, including numerous human and animal figurines. Also, the treatment of the dead is strongly ritualistic. In most cases, the deceased individual was placed in a flexed position beneath the floor of a dwelling, and the burial pit was then plastered over. Sometime later, the burial was exhumed and the skull was removed. The location of most of the detached skulls is unknown; only a few caches of 13 skulls with evidence of plaster have been recovered (cf. Bonogofsky, 2001).

Clearly, the Middle and Late PPNB was a period of prosperity at 'Ain Ghazal, as indicated by the presence of a rich variety of domestic and wild animal and plant resources, an unprecedented level of artistic achievement, numerous animal and human figurines, remarkable statuary, and highly evolved ritual behavior (Rollefson and Simmons, 1987; Simmons et al., 1988). Also, sophisticated architecture evolved during this period, and during the Late PPNB, virtual "apartment houses" were constructed to house up to three to four families (Rollefson, 1997). However, perhaps as early as the PPNC, and certainly by the Yarmoukian, a dramatic shift in the subsistence strategy occurred that led to the abandonment of the site (Köhler-Rollefson and Rollefson, 1990). From heavy reliance on domesticated plants and animals, but supplemented by wild resources, the economy changed to one that relied on pastoralism, with goats or sheep (or both) becoming the primary food source (Simmons et al., 1988). The areal extent of 'Ain Ghazal decreased significantly during the Yarmoukian, and the archaeological record suggests that the village became impoverished and may have been occupied on a seasonal basis.

The results of a geoarchaeological investigation at 'Ain Ghazal indicate that the landscape became unstable toward the end of the PPNB and especially during the PPNC and Yarmoukian periods (Mandel and Simmons, 1988). Also, there is evidence for increased aridity during these periods (Zielhofer et al., 2012). Erosion was stripping soil off the steep sideslopes above the site, and sheetwash was depositing the "soil sediment" on the footslopes and toeslopes, resulting in burial of successive occupations. So what drove the landscape instability? At 'Ain Ghazal, it is likely that nonirrigated cultivation and animal husbandry initially were complementary subsistence strategies before a critical population size was reached and before the local environment began to deteriorate (Simmons et al., 1988). As the economy shifted to a strong dependence on goats and sheep, it is likely that overgrazing affected the fragile environment and accelerated soil erosion. Degradation of the environment would have forced the inhabitants of 'Ain Ghazal to move their goat herds farther and farther away. In sum, the environmental degradation caused by over 3,000 years of intensive land use during the Neolithic, combined with aridification, may have rendered the landscape surrounding 'Ain Ghazal incapable of supporting a major agriculturally based community, leading to the abandonment of the site around 7,000 years ago.

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## AKROTIRI *AETOKREMNOS*, CYPRUS

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Akrotiri *Aetokremnos* is a collapsed rock shelter on the southern coast of Cyprus's Akrotiri Peninsula. The site is on a steep cliff overlooking the Mediterranean Sea, some 40 m below. Excavations at *Aetokremnos*, in 1987–1988 and 1990, uncovered a 1.0–1.5 m thick package of deposits preserved beneath massive roof-fall blocks. These deposits contained cultural features and artifacts in direct association with huge amounts (nearly 300,000 bones representing at least 505 individual animals) of extinct pygmy hippopotamus (*Phanourios minutus*) and pygmy elephant (*Elephas cypriotes*) representing at least three individuals, as well as numerous bird and shell remains (Simmons, 1999).

*Aetokremnos* is the oldest well-documented archaeological site in Cyprus. Full details of its radiocarbon chronology are provided in Simmons and Wigand (1994). A total of 36 radiocarbon determinations are available for the site. Three of these were from surface specimens, and the remainder was from sealed contexts. Materials dated included marine shell, *Phanourios* bone, sediment, and charcoal. Based on statistical analyses, *Aetokremnos* was occupied for a relatively short time centered around 11,800 cal. BP. Even with newly documented Pre-Pottery Neolithic A (PPNA) sites on the island (Manning et al., 2010; Vigne et al., 2011), *Aetokremnos* predates the Neolithic occupation by about 500 years.

A total of 1,021 chipped stone artifacts were recovered from *Aetokremnos*. Over 95 % came from subsurface contexts, many in stratigraphic association with burned and unburned bones. Small, well-made "thumbnail" scrapers dominate the assemblage of 128 formal, retouched tools. Other tools include additional scraper forms, burins, retouched pieces, truncations, notches, and microliths. All of these artifacts were manufactured using locally available materials.

Geoarchaeological investigations of *Aetokremnos* were undertaken during the course of the excavation, in part to answer the questions raised concerning the association of the cultural materials and faunal remains (Mandel and Simmons, 1997). Four major stratigraphic units, numbered 1–4 from uppermost to lowermost, were identified at the site, with cultural features and artifacts concentrated in Strata 2 and 4. The duration of human occupation, as represented by cultural deposits in these two strata, was relatively short, perhaps a few hundred years or less.

Most of the sediments that accumulated in the rock shelter are a product of roof fall, disintegration of bedrock (attrition), and wind action. In addition, a small volume of slopewash entered the back of the shelter through solution cavities and is confined to less than 5 % of the site. Although some of the strata have been slightly affected by leaching and clay translocation, there is no evidence of soil development in the shelter. The physical and geochemical properties of the strata indicate that the sediments and associated cultural materials rapidly accumulated on the floor of the shelter soon before the roof collapsed, isolating the underlying deposits from subaerial weathering and other site-disturbance processes. This explains why there has been very little mixing of artifacts and bones between Strata 2 and 4; the cultural deposits at *Aetokremnos* have near-pristine vertical and horizontal integrity.

In summary, *Aetokremnos* is significant for two reasons. First, it is among the best-documented ancient sites on any of the Mediterranean islands. Second, and more controversially, artifacts are associated with the extinct endemic island fauna, notably pygmy hippopotami. Prior to the discoveries at *Aetokremnos*, such an association had never before been demonstrated, and humans may have been partially responsible for the early Holocene extinction of these unique animals (Simmons and Mandel, 2007).

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## ALLUVIAL SETTINGS

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### Definition

The term alluvial geoarchaeology denotes the practice of geoarchaeology in fluvial drainage systems, with an emphasis on the discovery, excavation, and contextual analysis of archaeological records in alluvium, i.e., sediments deposited by water, and existing within varied alluvial settings.

### Introduction

The study of alluvial systems and their geologic records has been an important part of the earth sciences since the 1830s, when Charles Lyell focused on alluvial records as part of his famous *Principles of Geology*. In his *Antiquity of Man* (1869), arguably the first major work in geoarchaeology, Lyell recounted many discoveries of artifacts and fossils in alluvium, using these to present one of the first chronicles of human cultural and environmental history.

Since that publication, archaeologists and geologists have constructed an increasingly detailed record of human occupations in alluvial environments. The oldest known stone artifacts, 2.6 million-year-old flakes and cores, were recovered from alluvial sediments of the paleo-Awash River in Gona, Ethiopia (Semaw et al., 2003). Succeeding phases of cultural evolution are documented by Paleolithic finds in Africa and Eurasia that were preserved in alluvial deposits (van Andel and Tzedakis, 1996; Potts et al., 1999; Holliday et al., 2007; Rosen, 2008; Patnaik et al., 2009; Marder et al., 2011), and some of the most important sites bearing on the peopling of the New World are preserved in alluvium (Wagner and McAvoy, 2004; Haynes and Huckell, 2007; Mandel, 2008; Waters et al., 2011). In both the Old World and the New World, intense utilization of fluvial environments by sedentary agriculturalists has also been documented by geoarchaeologists (Rosen, 1997; Guccione, 2008; Huckleberry and Duff, 2008; Nials et al., 2011).

Today, it is both important and challenging to summarize this branch of geoarchaeology because so much highly productive archaeological research is conducted in alluvial settings. Accordingly, alluvial settings figure prominently in major works on geoarchaeology (Butzer, 1982; Needham and Macklin, 1992; Waters, 1992; Brown, 1997; Rapp and Hill, 1998; Holliday, 2004). There are three main reasons for this. First, humans have always exploited alluvial environments because they provide water, diverse food resources, fuel, and means of travel and transport. Second, alluvial sedimentation promotes burial and preservation of archaeological sites. Third, alluvial landforms, sediments, soils, and associated paleontological materials provide excellent opportunities to place archaeological records in temporal and environmental context. Significant overlap in the goals, strategies, and methods of alluvial geoarchaeology exists with geoarchaeological investigations conducted in other geologic settings, and therefore, consulting the cross-referenced entries in this encyclopedia will provide expanded discussions and illustrations of many issues considered here.

The goal of the following discussions is to provide an overview and guide to further study of both alluvial geology and how geoarchaeology is practiced in alluvial settings. This is supported by references to general works and specific investigations that illustrate major features of alluvial systems and many aspects and results of geoarchaeological research.

### Alluvial geology and geomorphology

Students of alluvial geoarchaeology can benefit from the extensive treatment of alluvial geology in both introductory and advanced texts. Streams and rivers are introduced in all textbooks on physical geology. Geomorphology texts, such as Bloom (2004) or Ritter et al. (2011), provide thorough reviews of alluvial processes and the resulting geologic records of landforms and bodies of sediment. Other recommended sources on alluvial geology include Schumm (1977) and Leopold (1994). A major focus of many syntheses is the responses by streams to climate change; these responses prove to be especially pertinent to the interests of archaeologists, who seek to document and understand ancient cultural responses to climatic and environmental changes over long intervals (Knox, 1983; Bull, 1991; Frederick, 2001; Macklin and Lewin, 2008). The following discussions will illustrate that geoarchaeologists also contribute directly to alluvial geology in the course of their research. First, an overview of alluvial geology is presented by way of an introduction to the major kinds of processes that have shaped alluvial geologic records; then the discussions turn to major issues in the field of alluvial geoarchaeology.

On the most general level, alluvial geology is the study of landforms, sedimentary deposits, and associated features that are the result of erosion, transport, and deposition within a drainage system. Drainage systems comprise a trunk stream and its tributaries, and they are defined by topographic catchments whose boundaries are in turn delineated by interfluves (essentially, ridges that divert surface runoff of precipitation into one or another drainage). The drainage basin for a given system extends from its headwaters to its termination in an ocean or lake basin. Streams and their tributaries exhibit marked changes in behavior and scale along a downstream (longitudinal) direction. Such changes in typical drainages include: (a) a decrease in channel gradient (steepness), (b) an increase in discharge (the volume of water per unit of time passing a point along the channel), (c) an increase in the sinuosity of the channel, (d) an increase in the load of the stream (the solid and dissolved materials carried in the water), and (e) an increase in sediment storage (alluvial deposits). Over time, a typical stream and its tributaries will erode down through the bedrock creating an increasingly large system of valleys that are connected at confluences. Stream valleys typically preserve sediment (alluvium) that was deposited in channels and on floodplains (the portion of the valley that is periodically inundated by floodwaters). Because archaeological sites are often buried in alluvium, deposits under floodplains and terraces are the target of archaeological surveys and subsequent excavations, as discussed below.

Most alluvial systems are subject to periodic and/or episodic changes in geologic activity. Floods are the most common kinds of change. The frequency and magnitude of floods vary considerably. In general, the common, smaller floods result in (a) the addition of sediment to floodplains (alluviation) when high water overflows a stream's banks and (b) minor shifts in channel positions. Over periods of centuries or even millennia, these changes often appear to have been quite gradual. However, large floods, as well as external forces such as climate change or tectonic activity, can effect more significant changes, including entrenchment of the channel into the underlying bedrock or older alluvium. Such incision can be accompanied by *floodplain abandonment*, which transforms the former floodplain into a terrace (a bench-like landform that stands above the new, active floodplain). Multiple terraces signify several episodes of valley entrenchment, with increasingly older sediments preserved under each higher terrace surface (Bull, 1990; Bridgland and Westaway, 2008).

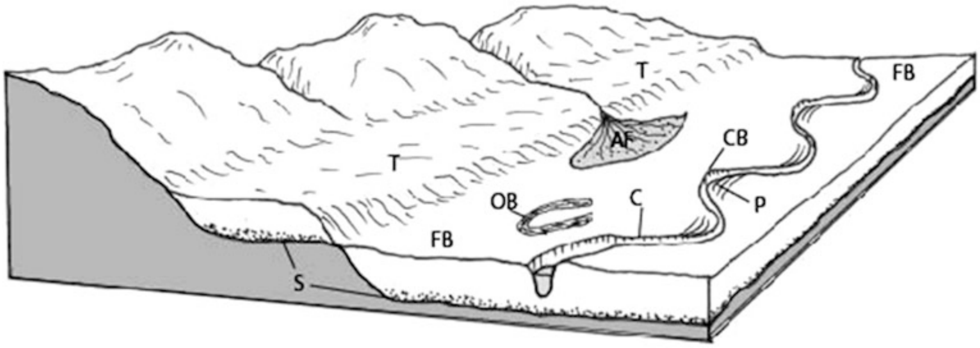
## Sedimentation on floodplains

The accumulation (aggradation) of sediments on the floodplains of streams and rivers is usually the most important aspect of alluvial geology for archaeologists simply because this is the means by which archaeological sites are buried and preserved (Ferring, 1986a; Ferring, 2001). Floodplain sediments register the response of the fluvial system to both internal and external agents, and therefore, they are a major focus for geologists who study alluvial records with regard to climate change, tectonics, sea-level fluctuations, and other factors. The most important differences in alluvial geology are caused by climatic and tectonic factors (Frederick, 2001). In terms of climate, it is important to contrast alluvial processes and geologic records that occur within humid environments (Ferring, 1990; Mandel, 1995; Ferring, 2001; Bettis et al., 2008; Guccione, 2008; Kesel, 2008) to those that occur within arid ones (Cooke and Warren, 1973; Patton and Schumm, 1981; Freeman, 2000; Waters, 2000; Cordova et al., 2005; Butzer et al., 2008; Harden et al., 2010). Tectonic controls on alluvial geology are frequently important, especially in ancient contexts (Bull, 1991; Noller, 2001), e.g., many of the important Lower Pleistocene archaeological records from East African Rift valleys come from alluvial settings that were subject to tectonic processes (Potts et al., 1999; Feibel, 2004; Sikes and Ashley, 2007; Feibel, 2008; Domínguez-Rodrigo et al., 2009; Feibel et al., 2009). Within these different settings, the varied contexts condition the general processes of alluviation, soil formation, and erosion on floodplains.

It is convenient to consider floodplain sedimentation in two major settings: in and near channels and farther from channels within the flood basin (Lewin, 1978). Different kinds and rates of deposition on a floodplain result in the construction of distinctive landforms called depositional geomorphic features; these include point bars, cutbanks, natural levees, and the flood basin (Figure 1). In addition to these geomorphic features, the properties and contents of the sediments (called sedimentary facies) are used to reconstruct the particular depositional setting, more properly called the sedimentary environment.

Alluvial sedimentary *facies* are "packages" of sediment in the geologic record that are defined by their texture (grain size), sedimentary structures (such as bedding), and their organic content (Miall, 1992). Facies analysis includes the description and study of those properties in order to identify and reconstruct the sedimentary environments responsible for their creation in space and time. The analysis is conducted together with actualistic comparisons to modern streams so that characteristics of the older sediments can be compared to those typical of ongoing depositional processes. This is especially important in the study of geoarchaeological records, because both past occupation potentials and site formation processes vary considerably by specific depositional environment. Based on extensive studies, many alluvial facies have been formally defined by sedimentologists (Reineck and Singh, 1980; Miall, 1992; Houben, 2007).

An exposure of sediments in a cutbank of the Trinity River in Texas illustrates a sequence of alluvial facies (Figure 2). The lower part of the section consists of steeply dipping beds of sand and silt that "fine upwards," i.e., become finer higher in the section; these were deposited on a point bar. As the channel migrated away from this location, the environment shifted to that of a flood basin, where episodic deposition of clays was accompanied by soil formation from ca. 2000 to 1000 BP (Ferring, 1990; Ferring, 1992). Later, the channel returned to this position, and the natural levee deposits (thin beds of sand and silt) accumulated. This is a common sequence of facies, which are stacked into a vertical "facies association" (Miall, 1992). Note that this sequence of sediments records a spatial shift in sedimentary environment because



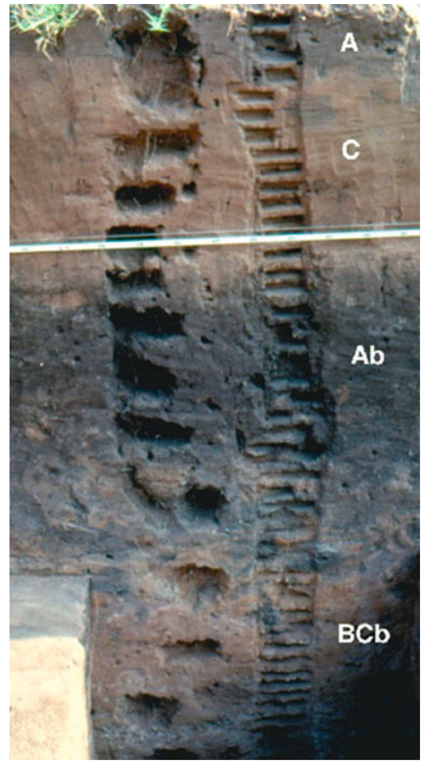

**Alluvial Settings, Figure 1** Geologic features of a meandering river valley. Note the major sedimentary environments: *C* channel, *P* point bar, *CB* cutbank, *FB* flood basin, *OB* oxbow lake, *T* terrace, *S* strath, *AF* alluvial fan. Point bars are locations on the inside, or convex, banks of a meandering stream where sediment tends to be deposited. Cutbanks are steep erosional surfaces on the opposite outside, or concave, banks of a meandering stream. Oxbow lakes are rounded bodies of water created when extreme meander bends in the river join and give rise to a straighter main stream and a curved cutoff filled with standing water. Straths are terraces previously etched into underlying bedrock prior to alluvial buildup within a valley.


**Alluvial Settings, Figure 2** Sedimentary facies of alluvium on the West Fork Trinity River in northern Texas. This cutbank exposes sediments of a Late Holocene point bar and floodplain, overlain by a recent natural levee.

meandering channels constantly migrate laterally across the floodplain. These normal variations in floodplain alluviation need to be documented prior to making unsubstantiated assertions, for example, suggesting that they reflect a change in climate. As discussed below, the prospects for finding preserved archaeological materials in a section like this are best in the floodplain clays, which accumulated for a longer period of time in a setting favored by Archaic and late prehistoric populations, ca. 3000–600 BP. The levee deposits accumulated after the arrival of Europeans.

Alluvial facies vary significantly in both space and time. Meander belts are the zone within valley floors across which meandering rivers periodically shift their courses; rapid sediment buildup along these meander belts can promote avulsion of the channel system to a lower part of the floodplain (Ferring, 1992; Törnqvist and Bridge, 2002; Phillips, 2011). Longitudinal (downstream) changes in facies are also common, owing to increases in discharge, changes in sediment load, and changes in bedrock geomorphic controls such as valley constrictions. Because of higher gradients, greater erosional potentials, and different vegetation patterns, alluviation in tributary streams can leave records that differ significantly from those in trunk streams. This is well documented in valleys of the Great Plains, which contain rich archaeological records (Mandel, 1995; Bettis and Mandel, 2002; Bettis et al., 2008; Mandel, 2008).

The rate of sedimentation is a significant variable in the record of alluvial sediments and associated archaeological materials (Ferring, 1986a). Indeed, the rate of sedimentation largely defines the potential for preservation of alluvium (Lewin and Macklin, 2003), as well as archaeological materials deposited on floodplains. Even without changes in climate or other external factors, sedimentation rates vary across floodplains, mainly in response to more rapid deposition of coarser (sand and silt) sediments near channels. When flooding rivers overrun their banks, the swift moving water slows down as it escapes the confines of its channel, and coarser sediments entrained by the formerly rapid flow are dropped closer the channel. This deposition results in the construction of raised meander belts, as mentioned above. Slower deposition in distal floodplain settings (i.e., farther from channels) is usually associated with finer suspended sediments (clay and silt) that are carried a greater distance away by floodwaters. Rates of sedimentation are also controlled by geomorphic factors, such as valley constrictions that impound floodwaters. Significantly, overall rates of floodplain aggradation may "wane" in response to long-term aggradation, which effectively raises floodplains above their channel bases. However, one of the most important implications of changing rates of sedimentation concerns soil formation on floodplains (Ferring, 1992).




**Alluvial Settings, Figure 3** Profile at Delaware Canyon, Oklahoma, with an overthickened, buried soil (Ab). This soil preserved stratified Plains Woodland artifacts, faunas, and features. The small sample holes were for pollen analysis, while the larger samples were used for physical and chemical analyses of the sediments and soils. The lack of visible stratigraphy within the soil horizons mandated the use of arbitrary 5 cm levels for excavation.

## Alluvial soils

The study of alluvial soils is important for both geologic and archaeological investigations. Alluvial soils, like those that form in other environments, are indicators of surface stability (Holliday, 1992; Birkeland, 1999; Holliday, 2004). On floodplains, soil formation signifies reduced rates of deposition, which allows time for soil profiles to develop. While some alluvial soils simply register a shift in sedimentary environments as mentioned above, regional climatic changes resulting in penecontemporaneous soil formation in multiple drainages are well documented (Ferring, 1990; Ferring, 1992; Mandel and Bettis, 2001; Beeton and Mandel, 2011). Particularly in North American settings, where archaeological records are dominantly Holocene in age, floodplain soils are generally weakly developed. Soils with A-C profiles are the most common, although weakly developed B horizons (Bw, Bk, or Bt) are found in some settings (Holliday, 2004).

Especially for geoarchaeological investigations, it is important to consider that floodplain alluviation and soil development often occurred simultaneously. In these cases, soil development alters the original properties of the sediment. This situation led to the definition of "pedofacies" (Kraus and Brown, 1988) or "soil facies" (Holliday, 2004, 79), which recognizes variations in alluvial sediments caused by the formation of soil features. This is particularly common in soils formed on floodplains. One consequence of time-transgressive deposition and soil development is the formation of *cumulic soils* (Birkeland, 1999, 165; Holliday, 2004, 90). A common result of cumulization is the development of overthickened soils, particularly thick A horizons. An example developed in Late Holocene alluvium at Delaware Canyon, Oklahoma, is shown in Figure 3. The overthickened buried A horizon (Ab) formed roughly between 1900 and 1000 BP, and it contains well-preserved artifacts and faunas of Plains Woodland groups who repeatedly camped on the floodplain of Delaware Creek (Ferring, 1986b). In the photo, note that the Ab horizon is underlain by a weakly developed B horizon. Prominent krotovina (rodent burrows), with several generations of fill, testify to post-occupational disturbance. The fill from these burrows was excavated separately and discarded to minimize the effects of mixture of bone and artifacts between occupation surfaces. Analysis of alluvial soils is a key component of site formation studies, as discussed below.

## Site discovery

Methods for archaeological survey in floodplain settings must be tailored to the fact that many sites are deeply buried. Perhaps the most common means for discovering deeply buried sites is by careful examination of natural cutbank exposures (Figure 3). During such surveys, particular attention is paid to sedimentary facies and buried soils, which are important guides to both the age and depositional environments pertinent to site discovery. Well-established stratigraphic-soil sequences have been developed to target particular temporal/cultural periods. On the Great Plains, survey strategies have been developed for the whole range of cultural periods, including Paleoindian (Bettis et al., 2008; Mandel, 2008), Archaic (Mandel, 1995), and Late Prehistoric (Ferring, 1990). It should be noted that surface surveys of large, complex river systems are also an important research strategy (Wells, 2001). An exemplary case study is the survey of sites in the Missouri, Red, and Mississippi River valleys by Guccione (2008). Hundreds of sites were located in diverse geologic settings, resulting in a comprehensive analysis of settlement intensity and settlement patterns over the Holocene.

Both mechanical techniques and remote sensing are also useful in the survey of alluvial deposits. Coring and trenching are frequently used to discover buried sites under floodplains. Both methods were used in the Ohio River Valley to define geologic contexts as well as discover deeply buried Woodland and Late Prehistoric age sites (Stafford and Creasman, 2002). Similar approaches were used to explore alluvial deposits that buried a series of Middle Holocene (ca. 5000 BP) Archaic mounds in the lower Mississippi Valley (Arco et al., 2006). Rosen (1997) used trenching as well as natural exposures to locate and study Neolithic-Bronze Age sites in Turkey. Remote sensing techniques include resistivity, magnetometry, and ground-penetrating radar (Kvamme, 2001). These approaches are best geared to defining the lithology and contacts of buried alluvial units, as a prelude to mechanical testing.

## Alluvial terraces

Alluvial terraces are landforms created by the abandonment of a floodplain by means of channel incision or entrenchment (Bull, 1990). This process may be caused by tectonic uplift, climate change, or, in localities near coasts, falling sea level (Bull, 1991). When alluvial deposition slows or ceases, permitting a transition to surface stability, the sediments below the terrace surface are subjected to new soil-forming environments. Soils on progressively higher, older terraces (Figure 4) have developed over longer periods, resulting in a soil chronosequence running up through the terrace structure (Birkeland, 1999, 192). Because of the relatively recent peopling of the New World, sites buried in terrace deposits are uncommon in North and South America; however, the surfaces of terraces were favored locations for Late Pleistocene and Holocene occupations because of their proximity to streams coupled with protection from floods (Ferring, 1992; Guccione, 2008). Archaeological records within terrace deposits are quite common in the Old World because of the much greater time depth of occupations compared to the New World (van Andel and Tzedakis, 1996; Cordova et al., 2005; Schuldenrein, 2007; Patnaik et al., 2009).

## Alluvial fans and colluvium

Sediments derived from steep valley slopes are frequently deposited along the margins of valleys, where they can accumulate on terrace surfaces or become interstratified with floodplain deposits. These deposits include generalized slope deposits called *colluvium* and more discrete bodies called *alluvial fans*, described below. Because these deposits represent aggrading surfaces usually above the active floodplain, they were frequently occupied and are generally good environments for the preservation of archaeological sites. Colluvium is most often preserved as "aprons" along the base of slopes, underlain by sediments that accumulated as a result of gravity (creep or mass movements) and/or sheet wash (Bloom, 2004). Changes in sediment supply, precipitation, and vegetative cover are among the factors that led to alternating periods of rapid deposition and periods of slower deposition with soil formation along valleys of the Midwestern United States (Bettis, 2003). Numerous archaeological sites are preserved in those colluvial deposits. At the famous Paleolithic Kostenki-Borschevo sites in Russia, colluvial deposits are interstratified with alluvium, loess, and volcanic ashes (Holliday et al., 2007). In China, a Middle-Upper Pleistocene series of terraces, each with associated alluvial fans, has been defined and dated as part of an intensive survey for Paleolithic sites (Lu et al., 2010).

Alluvial fans comprise major sedimentary environments that have been studied in many settings, ranging from humid to arid (Reineck and Singh, 1980, 298; Miall, 1992). In contrast to colluvium, alluvial fans are distinct, fan-shaped depositional landforms that develop at the intersection of steep tributaries with either terrace surfaces or floodplains. In desert settings, adjacent alluvial fans often coalesce into continuous features called *bajadas* (Bloom, 2004). Alluvial fans are characterized by intermittent sedimentation, with frequent shifting of channel/gully positions, and a general fining of sediment texture from proximal to distal positions down the fan to the bottom, where closed playa lakes are common. Especially in


**Alluvial Settings, Figure 4** Alluvial terraces and soils: (**a**) Late Pleistocene terrace of the Tedzami River near Gori, Republic of Georgia; (**b**) Late Pleistocene terrace deposits and soil on the Trinity River near Dallas, Texas. The soil of the Trinity River deposits has been forming since the Late Pleistocene floodplain was abandoned by incision ca. 22–25 Ka. Surficial archaeological sites, often palimpsests created by the superposition of repeated occupations, are common on the terrace surface, while fossils of extinct fauna are preserved in the underlying sediments of the sandy channel facies.

humid environments, such as in the Midwestern United States, alluvial fans have built up over earlier Holocene deposits, preserving numerous archaeological sites underneath (Bettis and Mandel, 2002; Bettis, 2003). Periods of slower fan aggradation were accompanied by soil formation, which assist in stratigraphic correlation among different fans. Alluvial fans were commonly chosen for occupation from the Early to the Late Holocene, as illustrated by excavations at the Koster and Napoleon Hollow sites in the Illinois River Valley (Wiant et al., 1983.) Alluvial fans and bajadas are very common in the western deserts of the United States, and they are prime targets for archaeological surveys (Waters, 1992, 2000; Nials et al., 2011).

## Eolian deposits

Eolian sands or loess are frequently found in association with fluvial deposits, especially in the Midwestern United States. Pleistocene loess is a major source for younger alluvium that now fills river valleys (Mandel, 1995; Mandel and Bettis, 2001; Bettis and Mandel, 2002; Bettis et al., 2008). Eolian sands accumulated along drainages in the southwestern United States and buried early Holocene sediments in the "draws" of the Southern High Plains (Holliday, 1995). At the Mockingbird Gap site in New Mexico, Clovis artifacts were buried in eolian sands along Chupadera Draw (Holliday et al., 2009). Research in those settings illustrates the careful geologic analysis of sediments and soils necessary to reconstruct sedimentary environments and site formation processes, both of which are important goals of most geoarchaeological studies.

## Paleoenvironmental studies

Alluvial deposits often preserve important evidence of past environments, which is frequently studied in concert with archaeological investigations. As described above, alluvial facies provide records of sedimentary change, especially in response to environmental shifts (Knox, 1983; Bull, 1991; Bettis et al., 2009; van de Wiel et al., 2011), and alluvial soils are also used extensively as part of paleoenvironmental studies (Holliday, 2004). Study of stable isotopes of carbon and oxygen is conducted on both organic matter and pedogenic carbonates in alluvial soils (Humphrey and Ferring, 1994; Nordt, 2001; Sikes and Ashley, 2007). Changes in patterns of sedimentation as well as soil formation on floodplains need to be investigated first with respect to normal shifts in sedimentary environments (Figure 3), however.

## Site formation processes

Site formation studies are important in virtually all geoarchaeological contexts (Butzer, 1982). In alluvial settings, formation processes and formation histories are complex, owing to different rates and patterns of sedimentation and exposure on floodplains and terraces (Ferring, 1992; Ferring, 2001). In the main, floodplains are good formation contexts because burial occurs by low-energy, post-occupational deposition. However, rates of sedimentation vary markedly both longitudinally (downstream) and in different sedimentary environments within shorter reaches of a valley (Ferring, 1986a). Rates of sedimentation are important to document, for they exert strong controls on formation processes during and after occupations, often resulting in marked differences in artifact density and bone preservation among sites.

Sites in alluvial settings are subject to many weathering and disturbance processes, including bioturbation and pedoturbation (Wood and Johnson, 1978), which highlights the need for careful analysis of both sediments and soils, as at the Cactus Hill site (Wagner and McAvoy, 2004) and the Big Eddy site in Missouri (Hajic et al., 2007), both of which contain important records of Paleoindian occupations. There are often strong textural controls on formation processes. Sites that formed in sandy alluvium may be more prone to artifact trampling and bioturbation by insects and micromammals (see Figure 3). Fine-grained (clay-silt) sediments, common to floodplains, are more prone to pedoturbation by shrink-swell of vertisols and turbation by earthworms. Field observations and standard textural-chemical lab analyses are often supported by micromorphology, providing detailed evidence about sedimentary environments, soils, and anthropogenic features (Courty, 2001; Macphail and Cruise, 2001; Domínguez-Rodrigo et al., 2009). At the Friedkin site in Texas, micromorphology was applied to study possible effects of pedoturbation within Paleoindian and "pre-Clovis" deposits (Waters et al., 2011).

## Stratigraphy and dating

Alluvial records often provide excellent opportunities for establishing detailed chronologies for sediments and their entrained archaeological and paleoenvironmental data (van Andel and Tzedakis, 1996; Frederick, 2001; Macklin et al., 2002; Holliday, 2004; Feibel, 2008). As in other settings, most efforts at dating begin with stratigraphic studies of landforms, sediments, and soils. Morphostratigraphy addresses the sequence of alluvial landforms – including terraces – and alluvial fans, as well as depositional landforms such as floodplains, natural levees, cutoff channels, and oxbow lakes (Wells, 2001). The stratigraphic relations of these landforms are usually established by field description and mapping; however, the use of remote sensing (such as air photos and satellite images) is an increasingly productive approach (Guccione, 2008). In many cases, buried soils are critical stratigraphic markers, both within and between drainages (Holliday, 1995; Holliday, 2004). Allostratigraphic units are formally defined stratigraphic units in alluvial contexts (Miall, 1992; NACSN, 2004). These are packages of alluvial sediments, often comprising different facies, which are defined on the basis of bounding discontinuities, such as soils (representing intervals of stability) or erosional disconformities (representing intervals of sediment loss and the creation of abrupt discontinuities within the stratigraphic sequence). Although these are lithostratigraphic units – defined on the basis of sedimentary units in contact with one another – they also provide the necessary framework to support sampling for chronometric dating, leading to the definition of chronostratigraphic units.

Absolute dating of alluvial deposits employs a range of specific methods that are chosen to meet the availability of datable materials as well as the age range of the deposits. Radiocarbon dating is the most commonly employed method for deposits less than about 40,000 years old; however, optically stimulated luminescence (OSL) is increasingly used on silicate fractions of sediments, despite the generally high error factors (Holliday et al., 2007; Waters et al., 2011). For older deposits, uranium-thorium dating of pedogenic carbonates (Sharp et al., 2003) and Ar/Ar dating of associated volcanic rocks and sediments are employed (Feibel et al., 2009; Zaim et al., 2011).

In the central and eastern Great Plains, comprehensive stratigraphic sequences (lithosequences and chronosequences) of Late Quaternary alluvial deposits have been established, resulting in a framework for the discovery and study of archaeological records (Bettis and Mandel, 2002). A detailed stratigraphic framework has been developed for locating Paleoindian sites in the central Great Plains by Mandel (2008); a stratigraphic basis for site discovery was also developed for the Cottonwood River Basin in Kansas (Beeton and Mandel, 2011). Other useful examples of alluvial stratigraphy include the work in the lower Mississippi Valley (Kesel, 2008), the upper Mississippi Valley (Bettis et al., 2008), and in Holocene deposits in France (Berger, 2011). In the southwestern deserts of the United States, complex alluvial stratigraphic records have been established on the basis of both lithostratigraphy and radiocarbon dating (Waters, 2000). An excellent example is the work done in the San Pedro Valley (Arizona), where Haynes (2007) conducted detailed stratigraphic-dating research at the famous Murray Springs site (Haynes and Huckell, 2007). There, a superb record of Clovis activities was recovered at the base of a thick alluvial sequence (Figure 5).

## Summary

This brief summary of alluvial geoarchaeology has demonstrated that many important records of human history are preserved in sediments and on landforms created by streams. Although much geoarchaeological research is conducted in other geologic settings, many archaeologists and the geologists/geomorphologists they collaborate with will work in alluvial settings at some time in their career. For them, much can be learned from the older, important works, as well as the many recent examples of research cited here. This is especially true for archaeologists engaged in Cultural Resource Management (CRM), since many land use projects impact archaeological records in alluvial settings. Both CRM investigations

**Alluvial Settings, Figure 5** Alluvial deposits along Curry Draw, Arizona. Note the vertical walls of the modern arroyo, typical of desert streams. Clovis artifacts and fossils of numerous extinct megafauna were found just below the prominent "black mat" in the lower part of the section. These have been dated to ca. 10940 BP (Haynes, 2007).

and grant-supported research should exploit the contributions of alluvial geologists and geoarchaeologists as they design and implement research strategies. The extensive body of published research on alluvial geoarchaeology, some of which is cited here, is an important resource for researchers developing programs of site discovery, excavation, and contextual study.

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## Cross-references

Big Eddy Site, Missouri
Cactus Hill, Virginia
Chronostratigraphy
Colluvial Settings
Eolian Settings: Loess
Eolian Settings: Sand
Geomorphology
Koster Site, Illinois
Optically Stimulated Luminescence (OSL) Dating

Oxygen Isotopes
Paleoenvironmental Reconstruction
Pre-Clovis Geoarchaeology
Sedimentology
Site Formation Processes
Site Preservation
Soil Geomorphology
Soil Micromorphology
Soils
U-Series Dating

## AMINO ACID RACEMIZATION

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### Synonyms

Amino acid geochronology; Amino acid racemization; Aminostratigraphy

### Definitions

*Amino acid racemization*: a spontaneous reaction describing the interconversion between the chiral forms of an amino acid.

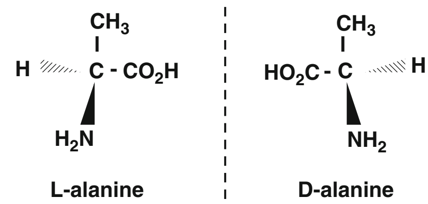
*Chiral*: describes molecules that may exist as mirror images of themselves that are nonsuperimposable; such molecules exhibit chirality.

*Enantiomer*: one of a pair of nonsuperimposable mirror images; also called an optical isomer.

*Stereoisomer*: molecules that possess the same elemental composition but different three-dimensional arrangements of atoms.

*Diastereomer*: a stereoisomer that is not a mirror image, that is, not an enantiomer.

Amino acids are the building blocks of proteins. They are found in all living tissues and can be preserved in fossil biominerals such as bone, teeth, and shells. The 20 naturally occurring amino acids all have a central carbon atom (the α-C) with four attached groups: an amino group ($NH_3$), a carboxylic acid group (COOH), hydrogen (H), and a side chain (R) that defines the type of amino acid. In glycine, the side chain is H, but for all other amino acids, the α-C has four different groups. The four distinct groups connected by single bonds make the α-C a chiral center, meaning that it can exist as two stereoisomers: the *levo* (L-form) and *dextro* (D-form), named after the optical activity of glyceraldehyde. Such stereoisomers are enantiomers because they are not only chemically identical, but they are also nonsuperimposable mirror images of each other (Figure 1). In living organisms, proteins are almost exclusively made from the L-form. However, this artificial dominance of the one form is unstable, so after death, a spontaneous reaction occurs to redress the balance. The extent of amino acid racemization (AAR) is recorded as a D/L value; AAR continues until a dynamic equilibrium is reached (usually D/L = 1). Depending on the amino acid, this process can take thousands or millions of years and therefore is applicable over Quaternary timescales. First applied to fossil shells (Hare and Abelson, 1968), AAR geochronology measures the extent of this degradation in fossils as an index of relative age (an aminostratigraphy), which can provide calibrated ages in combination with known-age samples or detailed temperature records.




**Amino Acid Racemization, Figure 1** L- and D-amino acid structure of alanine. Bonds depicted as hatched wedges go into the page, while those that are thick wedges come out of the page. The central carbon atom has four different functional groups attached to it; it is therefore a chiral center, and two chemically identical, but nonsuperimposable, mirror images can occur: L- and D-alanine.

Protein degradation consists of a series of chemical reactions that are dependent not only on time but also on environmental factors. The original protein composition is important, so AAR will occur at different rates in different species, precluding direct comparison in most cases. Environmental factors (e.g., temperature, pH, availability of water) can also affect AAR rates, leading to a focus on analyzing "closed-system" protein from fossil samples (Towe, 1980). A chemically protected organic fraction found in mollusk and egg shells (the "intracrystalline" fraction) appears to be shielded from the environment and does not lose any material through leaching, meaning that the protein degradation within this fraction is solely time and temperature dependent and therefore predictable. This technique has been particularly successful in dating carbonate fossils (shells, eggshells, foraminifera, ostracods). Advances in chromatography, preparative methods, and choice of material for dating have resulted in greatly improved temporal resolution, demonstrating the technique's potential for developing regional Quaternary chronologies around the world (e.g., Parfitt et al., 2005; Wehmiller, 2012).

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## ANALYSIS OF CARBON, NITROGEN, PH, PHOSPHORUS, AND CARBONATES AS TOOLS IN GEOARCHAEOLOGICAL RESEARCH

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### Introduction

In the context of archaeological research soil/deposit chemical analysis should be viewed as an additional data set or tool for interpreting the archaeological record. Because chemical signatures are not exclusively anthropogenic (they are not uniquely of human construction like artifacts), there is always a non-anthropogenic component or effect. Human activity either indirectly modifies a soil's chemical characteristic, as with pH, or it directly adds or subtracts material creating an anomaly by altering the amount of carbon, phosphorus, nitrogen, or carbonates in the deposits. Anomalies can only be detected if there is baseline data that characterizes the deposits prior to human intervention. This is accomplished by setting up control sampling locations or, if that is not possible, obtaining background data from preexisting sources (e.g., from sources like Shacklette and Boerngen, 1984). Interpretation of chemical data in archaeological contexts involves comparisons to control samples and an understanding of the evolution and maintenance of the anthropogenic soil anomaly (Carr, 1982). This is no small feat given the complexity of temporal and spatial occupation histories at many archaeological sites and the complex pedogenic response over time to anthropogenic activity.

Because this entry is about soil chemical analysis in archaeology, it seems appropriate to define soil from a soil chemist's perspective:

> Soils are multi-component, open, biogeochemical systems containing solids, liquids and gases. That they are open systems means they exchange both matter and energy with the surrounding atmosphere, biosphere, and hydrosphere. These flows of matter and energy to or from soil are highly variable in time and space but they are the essential fluxes that cause the development of soil profiles and govern patterns of soil fertility. (Sposito, 1989, 3)

The definition emphasizes that soils are open systems that adjust to variations in input. Knowing or hypothesizing about those adjustments after anthropogenic input over archaeological time scales is important for interpreting chemical data from archaeological contexts. The state factor's model of soil formation first developed by Jenny (1941) and advanced in geoarchaeology by Holliday (1994, 2004a) is an excellent conceptual framework for interpreting soil chemical data in archaeological contexts. The model consists of five external factors that govern soil formation. They are (1) climate, (2) organisms (plants and animals), (3) relief (landscape position), (4) parent material (anthropogenic and non-anthropogenic deposits), and (5) time. Both these factors and soil-forming processes vary, resulting in changes in soil morphology, hydrology, and chemistry. The human animal can be considered with all the other organisms involved in soil formation or, perhaps, more appropriately as the sixth factor. Human populations, although they are just a player in the ecological drama, are the dominant one. They modify all of the factors of soil formation in major ways at scales from a single dwelling to the global climate (Hooke et al., 2012).

#### Control sampling

Chemical analysis in geoarchaeology is comparative so it demands two or more data sets to be of much analytical use. Control samples should be taken in the field and analyzed to determine the background or natural level of the chemical of interest. This is equivalent to analyzing blanks in the laboratory, a standard and necessary procedure. The point of control sampling is to determine the non-anthropogenic or natural background chemistry of the soil off-site, and the state factor model is again a good conceptual guide. Thus, it is best to pick landscape positions off-site, where all of the state factors are similar to the sampling loci on the site. Multiple control locations may be necessary. In many situations (e.g., modern or ancient urban areas), finding a location that has not been previously utilized or occupied or that you know has not been utilized or occupied is difficult but should be attempted. Certainly a number of authors have advocated using control samples or have effectively used control samples in their research (see Proudfoot, 1976; White, 1978; Bakkevig, 1980; Carr, 1982; Sandor, 1992; Entwistle et al., 2000; Wells et al., 2000; Holliday, 2004a). In addition all samples should be analyzed using the same techniques/procedures and by the same laboratory to reduce unnecessary sources of error and uncertainty (see Holliday and Stein, 1989; Holliday et al., 2004c).

In many geoarchaeological investigations that use soil chemistry, a suite of chemical analyses is used to address research questions. For this reason geoarchaeological applications will follow the discussion of each of the chemical techniques.

### Carbon/organic matter

#### Sources and transformations in soils and deposits

Carbon occurs in soils in organic and inorganic forms (Stevenson and Coles, 1999). Organic forms occur as living plants and animals and as the by-products of the decomposition of plants and animals referred to collectively as the soil's organic matter fraction (SSSA, 1997). Inorganic forms can also be added to the soil by plants that contain crystals of calcium oxalate or opaline silica (Weiner et al., 2002; Piperno, 2006; Prychid et al., 2008). Calcium oxalates would contribute some carbon to a total carbon assay. However, most inorganic carbon is derived from the parent material (carbonate rocks and dust) (Birkeland, 1984; Nelson and Sommers, 1982). In non-calcareous soils almost all of the carbon is in the organic fraction of the soil (Nelson and Sommers, 1982). Carbon is a part of organic matter that is introduced into the soil by natural process and anthropogenically as plant tissue with a more minor contribution from animal tissue. Plant residue consists of 25 % solids that are made up of carbon, oxygen, hydrogen, and ash (Brady, 1974). The ash contains the macronutrients (phosphorus, potassium, calcium, magnesium, and sulfur) and micronutrients (zinc, iron, copper, boron, manganese, and molybdenum) as well as minor trace elements (Brady, 1974). These are relevant to studies of soil chemistry at archaeological sites as they form part of the anthropogenic and natural chemical load in soils and deposits. As soon as organic matter is added to the soil, it begins to decay. The rate of decay and the products of decomposition depend on the soil environment (Brady, 1974). In turn, the nature and strength of any anthropogenic anomaly depend on the nature and intensity of occupation and the soil-forming environment (Carr, 1982).

### Anthropogenic additions, subtractions, and transformations

Human populations are major players in cycling organic material in the environment. The organic carbon fraction is of interest in geoarchaeological studies because it is a component of building material (wood and adobe), food, waste, and a by-product of food preparation, material processing, and heating (e.g., charcoal) at human habitations and ultimately in archaeological deposits. It is continually moved from place to place in the process of food production, settlement construction, and waste disposal. As a result, it is added to the soil, directly and indirectly, in the form of waste from a variety of activities in and around settlements, for example, the dark earths in Amazonia (McCann et al., 2001) and Europe (Chapter "FTIR" in Courty et al., 1989). And it is removed from the soil in places where farming or resource extraction (removal of tress or crops), for example, occurs. The most significant anthropogenic transformation of organic matter is by burning. This reduces organic matter to the much more decay-resistant and carbon-rich charcoal. In chemical analyses charcoal is measured as a part of the organic matter or total carbon fraction of the soil. It can also be used, for example, to determine the species (Asouti and Austin, 2005; Marguerie and Hunot, 2007) of wood being exploited for fuel and building material or if the wood was collected dead or alive (Moskal-del Hoyo et al., 2010). Charcoal is only relatively stable. It can be degraded and disseminated into small particles in alkaline soils (Dufraisse, 2006; Braadbaart et al., 2009) and can be attached by soil fauna and flora (Thery-Parisot et al., 2010). Reduced particle size has implication for site formation processes and chronology as the charcoal is more mobile in the soil profile. Stein (1992) provides a general summary of organic matter in archaeological contexts.

### Analytical methods

Total carbon in soils can be determined by wet or dry combustion techniques (Nelson and Sommers, 1982). Note this technique measures all forms of both the organic and inorganic carbon in the soil. The basic principle is to drive off and capture the $CO_2$ and then measure the amount captured gravimetrically or titrimetrically. This is generally done with automated laboratory instruments designed for carbon analysis (see Nelson and Sommers (1982) for examples and procedures). Another measure of soil organic matter is near-infrared reflectance spectroscopy (see entry "Anthrosols" by Woods this volume).

The most commonly used procedures to determine organic carbon are Walkley-Black (Nelson and Sommers, 1982; Singer and Janitzky, 1986) and loss-on-ignition (Dean, 1974) techniques. With Walkley-Black the sample is digested in dichromate and sulfuric acid, and the amount of carbon is determined by titration or colorimetrically. This procedure uses strong acids and needs a laboratory setup to do the digestion.

Loss-on-ignition is a simpler procedure, is as accurate (Dean, 1974) as Walkley-Black, and can also be used to determine carbonate in the sample. The procedure consists of placing oven-dried soil in a small pre-weighed crucible and heating it in a muffle furnace to 550 °C, cool to room temperature in a desiccator and reweighed. The difference is the amount of organic carbon ignited. The sample and crucible are placed in the oven and reheated to a higher temperature to determine the carbonate content (see section on carbonates below). The number of samples that can be done at one time is only limited by the size of the muffle furnace. Loss-on-ignition can also be done using automated thermogravimetric analyzers, which can process many samples at one time with direct computerized calculations, producing immediate tables and plots of results.

## Nitrogen

Most nitrogen in the soil is associated with organic matter or soil humus (Brady, 1974) that can be slowly released by the actions of microorganisms and made available to plants. The soluble ammonium and nitrate is readily available to plants but is also easily leached from the soil. Because nitrogen compounds are rapidly fixed (unavailable to plants) and mobile (available but easily leached), heavily cropped soils need a constant artificial supply of nitrogen fertilizer especially in modern mechanized agricultural systems.

### Sources and transformations in soils and deposits

Inputs of nitrogen to the soil come from addition of organic matter during the process of plant growth and decay, fixed by microorganisms from the atmosphere, and brought in to the soil in the form of ammonium and nitrate salts by precipitation (Brady, 1974). Once in the soil nitrogen is generally immobile or fixed except for small amounts of inorganic nitrogen in the form of nitrates and ammonium nitrates. Some ammonium nitrogen is also fixed in the lattices of clay minerals where it is very slowly available to plants during weathering. These later forms are available to plants and are mobile in soil water. Most nitrogen is rapidly cycled (Stevenson and Coles, 1999), a process whose rate depends on soil conditions (factors) especially climate.

### Anthropogenic additions, subtractions, and transformations

Human activity alters the nitrogen cycle by adding organic matter (waste and garbage) or fertilizer/manure in some places and removing it in others (movement of plants and building material to settlements). Because nitrogen is added to the soil along with carbon and other elements when disposing of plant or animal waste or fertilizing agricultural fields, it creates an anomaly that is closely associated with organic matter (carbon) anomalies. As organic matter breaks down, much of the nitrogen is rapidly volatilized and lost to the atmosphere or becomes mobile in the soil water (Brady, 1974). The remaining nitrogen is fixed by clay mineral or combines with soil organic matter. Because nitrogen cycles rapidly, it may not maintain a anthropogenic anomaly over long time spans, so it is not a good indicator of anthropogenic load (Holliday, 2004a) except, perhaps, on young archaeological sites (Woods, 1982) or in arid areas (Homberg et al., 2005).

### Analytical methods

There are two types of analysis that deal with total nitrogen: Kjeldahl wet combustion and Dumas dry combustion (Bremner and Mulvaney, 1982). In the Kjeldahl analysis the nitrogen in the samples is converted to ammonia ($NH_4^+{-}N$) by heating in sulfuric acid in the presence of catalysts. The amount of nitrogen is determined by measuring the amount of $NH_3$ liberated from the digest when distilled in an alkali. Dumas analysis involves heating the sample with CuO and exposing the liberated gas to hot Cu to reduce the nitrogen oxides and then to CuO to convert the CO to $CO_2$. The $N_2{-}CO_2$ mixture is then collected and exposed to a concentrated alkali that removes the $CO_2$, and then the volume of $N_2$ is measured. Both methods are complex and have recovery problems that researchers should be aware of before choosing a procedure (see Bremner and Mulvaney, 1982). Automated N analyzers are capable of processing samples relatively rapidly and produce results comparable to the wet chemistry methods (Thomas et al., 1967; Schuman et al., 1972).

## pH

The measure of the activity of ionized H (H+) in the soil solution is called pH (Mc Lean, 1982). It is one of the most indicative measures of soil chemistry (Boul et al., 1989) and is important in determining (after Mc Lean, 1982) the (1) solubility and hence mobility of compounds in the soil, (2) the bonding of ions to exchange sites, (3) activity of microorganisms, and (4) availability of plant nutrients. The pH scale ranges from 1 (most acidic) to 14 (basic), 7 being neutral.

### Sources and transformations in soils and deposits

Soil pH is not an element or compound that can be added or subtracted from the soil but instead is a condition of the aqueous phase of the soil environment that is very dependent on the interaction and evolution of the soil-forming factors. Many chemical reactions, weathering trajectories, and soil–plant relationships are pH dependent. Because soil water system is open, external inputs of water (including its dissolved constituents) and organic and inorganic particles – both natural and anthropogenic – can rapidly change the soil pH (Sposito, 1989) and therefore the pedogenic trajectory and the maintenance of the anthropogenic anomaly.

### Anthropogenic additions, subtractions, and transformations

The degree to which soil pH is modified by anthropogenic additions depends on the initial soil pH, buffering, and pedogenic context. Anthropogenic modifications of pH are direct and indirect. Direct addition of wood ash, limestone (especially burnt), and shell maintains alkalinity (Cook and Heizer, 1965). Addition of organic matter indirectly lowers pH because the decay of OM produces acids (Brady, 1974). Soil pH is an important parameter for predicting the degree of bone preservation, including bone proteins used in DNA analysis, and metal and charcoal preservation in archaeological deposits (Tylecote, 1979; Gordon and Buikstra, 1981; Pate and Hutton, 1988; Nielsen-Marsh et al., 2007; Braadbaart et al., 2009; Adler et al., 2011). Sheppard and Pavlish (1992) have shown that among other soil chemical variables, pH is important in the weathering of chert. Soil pH is also one factor in determining the potential for preservation of phytoliths (see Piperno 2006; Cabanes et al., 2011). In most geoarchaeological investigations that use soil chemistry, pH is one of a suite of chemical analyses used to characterize the soil as background for interpretations.

### Analytical methods

Determination of pH is accomplished using either colorimetric or electrometric techniques (Mc Lean, 1982). Colorimetric techniques use dyes or acid–base indictors that react by changing color in different pH environments. In its simplest form the electrometric technique consists of a glass electrode that measures the hydrogen ion activity and a reference electrode that completes a circuit so voltage can be measured (Mc Lean, 1982). The pH is typically measured in a 1:1 soil–water mixture (see Janitzky 1986 or Mc Lean, 1982). Many portable colorimetric and electrometric systems are available for field measurement of pH.

## Phosphorus

The most widely used soil chemical technique in archaeological research is certainly the analysis of phosphorus. This is because humans are very proficient at concentrating P in and around places where they live and much of the P added to soils is considered fixed (Brady, 1974; Walker and Syers, 1976). The source of the P is the plant and animal remains and waste left at sites that ultimately ends up in the soil. The association of high soil phosphorus levels and human settlements was first documented in the 1920s by Swedish soil scientist, G. Arrhenius (see Eidt, 1985 or Wells et al., 2000 for brief history). Since that time, P analysis has been used in many archaeological contexts to aid in determining site and feature boundaries, intra-site activity areas, intensity of occupation, and types of land use (for recent studies, see Barba et al., 1996; Parnell et al., 2001; Fernández et al. 2002; Barba, 2007; Middleton et al., 2010; Roos and Nolan, 2012).

There are a number of reviews of archaeological/geoarchaeological research using phosphorus that should be consulted as an initial source before developing a research strategy that includes P analysis. The most recent and most thorough reviews can be found in Holliday (2004b) and Holliday and Gartner (2007). They cover basic chemistry, common methods of extracting and measuring soil P, and the use of soil P in chronosequence studies. Proudfoot (1976) provides a general review of the extraction procedures and chemistry of P in soils, anthropogenic additions, and sampling issues as well as an example of P analysis from an archaeological site in Britain. Bakkevig (1980) provides more of a cautionary tale pointing out the importance of understanding the natural P background and the geomorphic context of any sampling site. White (1978) also stresses the importance of having background data.

### Sources and transformations in soils and deposits

The chemistry of soil P is complicated, in part because the P anions can bind with a number of cations in the soil to form compounds where the P bond varies in strength. P chemistry is strongly pH dependent which in turn is dependent on the soil factors at a particular site and on the natural and anthropogenic evolution of the site. A detailed explanation of P chemistry is beyond the scope of this entry, so P will be covered in a simple way under the heading of additions, subtractions, and transformation.

Almost all of the phosphorus in the soil system ultimately came from weathering of the inorganic P minerals (primarily apatite) in the soil parent material (Walker and Syers, 1976). The soluble P is taken up by plants, and upon death, they add organic matter to the soil. Once the system is established, most of the soil phosphorus is contained in soil organic matter (Brady, 1974). Soil microorganisms mineralize the organic forms of P to soluble inorganic forms ($H_2PO_4^-$, $HPO_4^-$) that are available to plants and can be leached out of the soil with the soil water. These latter processes are ways P can leave the soil, although on landscapes that are not cropped, the P is recycled. Of course weathering continues and small amounts of P still enter the soil from that source.

Most of the phosphate anions that enter the soil quickly form calcium (Ca), aluminum (Al), or iron (Fe) phosphates. Which compounds form depends on the soil pH and the amount and kind of each cation present. Brady (1974) divides P compounds in the soil into three major groups: (1) readily available phosphates that are generally water soluble (non-occluded P); (2) slowly available P including newly formed Al, Fe, and Mn phosphates, Ca phosphates, and mineralized organic phosphates; and (3) very slowly available phosphates of Fe, Al, and Mn, apatites and stable organic phosphates. His view of P is from the perspective of agronomy and soil science, where most basic research on P in soils has taken place. Laboratory analyses designed to study P in soils reflect the kinds of P found in soil (see below). Anthropogenic addition of P to the soil is also held at different location in the soil so to detect the anthropogenic anomalies P must be extracted either totally or differentially by chemically targeting the different phosphate compounds.

Soil phosphorus is only relatively stable over time because as soil factors change in response to environmental change and pedogenic processes adjust, P can be removed from the soil system or reorganized within the soil (see Walker and Syers, 1976; Tiessen et al., 1984; Roberts et al., 1985). On geomorphically unstable landscape facets, where erosion or deposition is occurring, the retention of P and the post-depositional evolution of the any anthropogenic P anomaly change.

### Anthropogenic additions, subtractions, and transformations

Anthropogenic sources of P come from domestic refuse, food waste, plant and animal remains, human bodies (especially bones), human and animal excrement, and wood ash (Cook and Heizer, 1965; Carr, 1982; Woods, 1982). Human populations are a factor in the P cycle and as such alter the process of P cycling. These alterations can be detected in the soils on archaeological sites.

### Analytical methods

Analysis of P in soils has two stages. The first stage is extracting the P from the soil (Olsen and Sommers, 1982; Meixner, 1986a). The extractant used depends on which form or forms of P are being targeted. The second stage is the determination of the amount of P in the extractant. This is accomplished by using a colorimetric method. In P fractionation multiple extractants are used in sequence to determine the different forms of P in the soils.

Spot test or ring test is a qualitative measure of P that can be done in the field with simple tools and reagents (Gundlach, 1961; Eidt, 1973; Woods, 1975). The test uses a weak acid extractant to measure the available P. Color is developed on filter paper based on a qualitative scheme (see Eidt, 1973). The advantage of the spot test is fast, low-cost results, but the disadvantages are qualitative non-reproducible results (Holliday, 2004b).

Available P refers to techniques that extract the water-soluble P and weakly held P fractions (Olsen and Somers, 1982). This involves extracting the P with weak acid and developing color intensity that can be read in a spectrometer. Available P types are often referred to by the name of the person who developed them such as Olsen P, Bray 1, or Mehlich II tests. They are differentiated because they use different extractants. Available P can also be done in the field with a portable spectrometer (see Terry et al., 2000).

Phosphate fractionation is the process of sequentially extracting P beginning with the most weakly bound P using extractants that target specific P compounds (Olsen and Somers, 1982; Meixner, 1986b). As many as eight different fractions, grouped into non-occluded P (three extractions), occluded P (three extractions), calcium bond P (one extraction), and organic P (one extraction), can be involved (see Meixner, 1986b). Most P fractionations in geoarchaeological applications use a three-fraction extraction sequence developed by Eidt (1977). This is an intensive wet chemistry procedure that targets the weakly bound Fe and Al-P and the reabsorbed Ca-P as fraction I (Eidt, 1977). Occluded P is fraction II and calcium P and apatite are fraction III.

Total P can be determined by using very strong acids to completely digest the soil, and P is measured colorimetrically (Olsen and Somers, 1982; Meixner 1986c). Total P can also be measured using ICP spectrometry, usually as one of a suite of elements. The ICP measures the P content so the type of P measured still depends on the extraction procedure.

## Carbonates

The origin of carbonate in soils is either from eolian sources, inherited from calcareous parent material, or weathered from non-calcareous parent material (Birkeland, 1984). Pedogenesis results in carbonate accumulations in soils in arid and semiarid climate zones and in its removal from the soil system in humid and tropical climatic zones (Birkeland, 1984; Boul et al., 1989). Carbonates are often measured as a part of soil/deposit characterization by determining the presence or absence of free carbonate using a few drops of HCl or less often by laboratory analysis. Results are used to determine the presence or absence of an anthropogenic carbonate load by comparison of control samples or other regional soil data and, if carried a step further, to interpret the anthropogenic changes in the pedogenic trajectory relative to site formation processes. For example, carbonates can dominate the soil chemistry in part by their effect on pH which in turn affects artifact preservation, especially bone and shell, and the post-depositional evolution of any anthropogenic additions (e.g., see Weiner et al., 2002).

### Sources and transformations in soils and deposits

The source of the carbonates in soil is atmospheric dust containing carbonate and $Ca^{2+}$ ions (Machette, 1986; Birkeland, 1984) and carbonate in parent materials (limestone, gypsum, dolostone, loess, glacial deposits from carbonate terrain). Parent material weathering in non-calcareous soils cannot account for the large amount of carbonate in arid and semiarid soils (Birkeland, 1984). In arid and semiarid regions, pedogenic processes form calcic soil horizons (K horizons) (Birkeland, 1984; Machette, 1986). In humid and tropical soils with lower pH, the carbonate is disassociated and is leached out of the soil system or accumulates as minor secondary carbonates in the C horizon (Boul et al., 1989).

### Anthropogenic additions, subtractions, and transformations

Anthropogenic additions that may increase the carbonate content in soils or lead to the formation of secondary carbonates are limestone and dolostone for cooking and, in some cases, pottery manufacturing and/or food processing, building material (plaster and stone), wood ash, and shell (Cook and Heizer, 1965; Woods, 1982; Schiegl et al., 1996). The age of the archaeological site, soil conditions, and landscape position are some factors that affect the post-depositional modification of anthropogenic carbonate additions. For example, physical and chemical processes during pedogenesis may destroy or fragment shell or carbonate rock adding secondary carbonate to the soil or removing it from the soil system entirely. Soil – geomorphic and stratigraphic – studies at archaeological sites record the soil carbonate status for characterization purposes with little geoarchaeological interpretations. Woods (1982) interprets the high carbonate levels in a midden in Illinois to be the result of the addition of ash to the midden. Indirectly human activity (e.g., land clearing and agriculture) that causes geomorphic instability may result in wind erosion, which could also add carbonate to soil.

### Analytical methods

The simplest measure of the presence of carbonate in soil is to observe the strength of soil reaction to 10 % HCl. The strength of the reaction is measured by the violence of the effervescence. The more carbonate, the more violent the reaction.

The loss-on-ignition (LOI) (Dean, 1974) method is used to determine both OM and carbonate. A sample is placed in a furnace first to 550 °C to destroy the organic matter, cooled and weighed, then put back in the furnace and heated to 1,000 °C to drive off the $CO_2$ in the carbonate. The sample is cooled and weighed again to determine the percent carbonate. Dean (1974) compared the LOI method with acid extractions and then titration and with determination of total Ca with atomic absorption and found that they yielded very similar results. Thermogravimetric analyzers have now completely automated the above procedure.

In the acid neutralization method, the carbonates are dissolved in acid and the amount of carbonate is determined by titration (Nelson, 1982). The gravimetric method uses a Chittick apparatus to determine the volume of $CO_2$ evolved during acid digestion (Machette, 1986).

## Geoarchaeological applications

The section on applications begins with examples of the use of phosphorus in geoarchaeological studies. Phosphorus data have been used as a tool in geoarchaeological investigations for nearly a century, and the literature is relatively extensive (see Eidt, 1985; Wells and Terry, 2007). The treatment below is not comprehensive and attempts to group the investigations by type. Chemical analyses, including phosphorus, are a part of a suite of measures used in the study of the Amazonian dark earths and are not included here (Glaser and Woods, 2004; see Woods this volume). Most investigations focus on the spatial distribution of P anomalies on the landscape surface within and around sites. The goal of these studies is to find site boundaries or to identify activity areas within sites. This involves examining both positive and negative P anomalies.

Skinner (1986) investigated P levels at five archaeological sites in Ohio. The goal of the investigation is to determine if P can identify anthropic soils and locate site boundaries determined by artifact distributions. Three different extraction techniques are compared for available P and one for total P. The conclusion is that the reliability of P as an anthrosol indicator depends on the geomorphic and pedogenic context specifically whether or not a soil/site was subject to inundation (i.e., located on a floodplain).

Roos and Nolan (2012) used available P (Mehlich II extraction) levels from 131 samples at a late prehistoric village site in Ohio to map intra-site activity areas. They were able to identify a ring midden and plaza using P data supported by magnetic data and artifact distributions.

Schuldenrein (1995) used soil chemistry (pH, OM, K, Ca, Mg) including available P, total P, and P fractionation, to detect activity areas at two sites in contrasting environments: the semiarid plains and humid temperate woodlands, both in the USA. Comparisons of control sample series with on-site and feature sample series indicate anthropogenic anomalies are present at both sites and is most strongly characterized by levels of P and K or P and selected other measures depending on the physical and cultural context. Plots of the three P fraction loadings on ternary diagrams are proposed as a graphic means of differentiating types of activity areas.

Woods (1982) found the following chemical trends at archaeological sites in Illinois. Carbon (organic matter) and nitrogen level were higher in midden soils than in control soils and both decreased in magnitude with depth. He found pH levels to be significantly more alkaline than control samples due to the large amount of wood ash in the middens that in effect neutralizes the acidifying effect of decaying organic matter. He also attributed carbonates in the middens to the addition of wood ash in an alkaline environment. P is high in the middens and absolute levels correlate with soil texture with P levels higher in clayey soils.

A number of interdisciplinary investigations have been conducted at the Piedras Negras site and surrounding modern settlements in Guatemala. These studies all use a field test procedure based on a Mehlich II acid extraction and measurement with colorimetry modified for use in relatively primitive field conditions (Terry et al., 2000; Wells et al., 2000; Parnell et al., 2001). The investigation identified a good correlation between P levels, density of ceramics, and boundaries of disposal areas. Fernandez et al., (2002) and Terry et al., (2004) investigated soil chemical signatures in modern settlements and a Mayan archaeological site to explore the relationship between chemical data (P, pH, Mg, Na, K, and trace elements) and household human activities. Phosphorus was high in areas of food processing, consumption, and disposal. Food preparation areas had high levels of P, Mg, and K and were more alkaline, while food consumption areas had high P and Na and were more acid. Traffic lanes had low P and refuse disposal areas have high P.

Dunning (1993) used total P to distinguish different types of land use and P fractionation to differentiate between agricultural and nonagricultural soils. High P levels are interpreted as areas that were gardens and likely fertilized and areas with depleted P as places of more intensive field agriculture.

Sandor (1992) compared the morphological and chemical characteristic of terraced cultivated soils and uncultivated soils at a 1,000–1,500-year-old prehistoric site in New Mexico, USA. Cultivated soils lost organic matter, N, and phosphorus (total and moderately available) and lowered pH. In contrast soils in terraced fields in Peru have elevated levels, relative to uncultivated soils, of total and available P, nitrate nitrogen ($NO_2$-N), total nitrogen, and organic carbon. Soil pH tended to be more acidic due to the increased organic matter. The chemical data, supplemented the archaeological evidence and soil morphological data, indicating the agricultural soils in New Mexico were not amended or fertilized and the agricultural soils in Peru were amended and fertilized. More recently similar methods including chemical analysis of soils was applied on a more regional scale to Native American agricultural system in the American southwest (Sandor et al., 2007) and more specifically to prehistoric Zuni agricultural systems (Homberg et al., 2005). Note these studies are among only a few that measured any form of nitrogen in geoarchaeological contexts (also see Woods, 1982).

Cavanagh et al. (1988) used HCl-extractable P data to map boundaries of sites in Greece. A positive correlation was found between high pottery sherd densities and high P levels.

The following investigations examine P distributions stratigraphically. Lippi (1988) used stratigraphic data (including artifacts), obtained from cores, and P data, obtained using the field ring test, to map paleosols and activity areas at the Nambillo site in Ecuador. The strata and soil description and P data provided an excellent framework for planning excavations and for making interpretations of land use on the buried landscape surfaces.

Katina (1992) used fractionation to test Eidt's ideas about the correlation of total P with intensity of land use and the use of fraction II/I ratio to determine relative time elapsed since phosphate enrichment. Results of the fractionation were very difficult to interpret because of the land-use palimpsest, but the total P and fraction II/I ratio was used to support soil landscape degradation during the Bronze Age followed by less intensive use during the Middle Ages.

Davidson (1973) used total P (fused with sodium carbonate and measure colorimetrically) from a tell stratigraphic sequence to measure intensity of occupation. P indicates that the (1) intensity of occupation increased up section and (2) the tell sediments have higher P than the local alluvium. He concluded that "phosphorus analysis confirms what might be expected-the tell evolved as a result of occupation and thus the activities of people who occupied the site.... accounts for the growth of the tell" (Davidson 1973, 146).

Bakkevig (1980) claims to get good results from the spot test in part because large numbers of samples can be processed quickly allowing a researcher to obtain data from a large area. The research questions involved correlation of land use with P levels and identifying cattle trails.

Ahler (1973) investigated the distribution of total P (perchloric acid/nitric acid digestion), available P (Brays Strong P test), OM (Walkley-Black), and pH from a stratigraphic sequence at the Rogers Rockshelter in Missouri. Results of the chemical analysis are compared with the distribution of lithic debris and micro-debris (sand-sized material of cultural origin). Ahler's results point out the importance of context for interpreting the chemical data. There is a strong correlation among lithic debris, micro-debris, and total P throughout the sequence and a strong correlation with available P and total P in the lower part of the sequence. The difference between the upper and lower stratum is due to higher sedimentation rates during the accumulation of the lower stratum not allowing pedogenesis to alter the distribution of the available P. It is concluded that total P is more useful for locating intra-site activity areas and available P is more useful for subsurface detection of sites and buried soils especially in strata with pHs similar to those at Rogers shelter.

## Conclusions

This brief overview of the uses of carbon, nitrogen, pH, phosphorus, and carbonate analysis in geoarchaeological investigation is far from exhaustive but hopefully illustrated the potential such analyses have for answering archaeological questions. When formulating research questions that involve data generated by chemical analysis, the plan should always have some type of control sampling and an understanding of the physical context of the samples. Control samples are necessary because all of the elements, compounds, and measures covered in this overview occur naturally without any anthropogenic input. So by default the analysis has to be comparative. Context is always important but it is particularly important for chemical analysis because of the multiple physical (stratigraphic/pedogenic), chemical, and anthropogenic transformations that occur during and after human occupations. In many cases the evidences for some types of human activity are all or in part chemical signatures and as such are a valuable tool for targeted geoarchaeological investigations.

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## ANTHROSOLS

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### Definition

Soils or sediments exhibiting significant chemical inputs as well as obvious physical changes resulting from human activity are called anthrosols.

### Introduction

In the FAO (2006) soil classification system, anthrosol is one of the major soil groupings for a broad array of soils "in which human activities have resulted in profound modification or burial of the original soil horizons" (p. 61). Anthrosols vary widely in their physical and chemical characteristics, and few traits are universal. There are several characteristics that are common or that serve as clues to the presence of significant modification due to human activity. The most obvious is the presence of archaeological debris within the soil, in particular organic detritus such as bone and charcoal in a surface horizon, i.e., they tend to be associated with middens. Other physical features, typically applying to surface horizons, include: abrupt, smooth boundaries between horizons or layers; abrupt, laterally discontinuous layers; and dark matrix colors (low value and chroma in the Munsell color system) extending to greater-than-expected depths for natural soils in the area (following Collins and Shapiro, 1987). The greater-than-expected depth is usually due to artificial upbuilding. Chemical signatures include higher-than-expected values of organic matter relative to natural soils and, in particular, phosphate (see below). Anthrosols may also have been subjected to some form of pedogenic alteration albeit relatively minor pedogenesis in many instances.

### Types of anthrosols

Anthrosols can include a wide array of soils, but three types have been described at some length: Plaggen, Dark Earths, and Terra Preta. Various other kinds of middens may also qualify as anthrosols.

*Plaggen soils* are most common on the sandy landscapes of the Netherlands, Germany, and Belgium, but similar soils are reported from other parts of northern Europe and Great Britain, Crete, Peru, and New Zealand (Kalinina et al., 2009; Van Mourik et al., 2011). They developed in the Middle Ages, probably around the tenth century (Pape, 1970; Heidinga, 1988; van de Westeringh, 1988). Manure was the preferred fertilizer, so in order to gather it, the floors of stables were strewn with forest litter, heather turves (slabs of heather cut from the ground), or grass sod to absorb the droppings from sheep and cattle. The mixture of manure, bedding, and mineral matter was then hauled out and strewn on fields. The mineral material brought in with the bedding sometimes provided additional nutrients. The mixture of manure, bedding, and mineral matter increased water-holding capacity and also deepened the plow zone, thus minimizing crop failure.

The *Dark Earth* is common in cities throughout much of Europe ("Urbic Anthrosols" of FAO, 2006). "Dark Earth" is a term applied to dark-colored, seemingly homogeneous urban deposits. In many ways, they can be considered anthropogenic sediments rather than soil, but they have undergone surface weathering and are typically considered a soil. In Britain, these soils are linked to late- or post-Roman, Saxon, Viking, Medieval, and perhaps post-Medieval occupation. General characteristics of Dark Earths include "an exceedingly uniform color" of dark grayish brown (with Munsell color coding 10YR 4/2) dry, to very dark gray (10YR 3/11) moist, mildly alkaline pH, some $CaCO_3$ (<10 %), 1–2 % organic carbon, some phosphate, and abundant midden debris (Courty et al., 1989, 262).

The *terra preta do Índio* ("black earth of the Indian") or simply *Terra Preta* soil of the Amazon Basin is a well-drained soil characterized by the presence of a thick black, or dark gray, topsoil which contains artifacts (Figure 1). They are found on upland areas adjacent to waterways along older terraces and also on interior uplands (Woods, 1995; Woods and McCann, 1999; Schmidt et al., 2014). In all settings, the dark colors of the Terra Preta contrast strongly with underlying subsoils which are red to yellow Ultisols, Oxisols, Spodosols, and eutrophic Oxisols (Sombroek, 1966; Smith, 1980; Lima et al., 2002). Terra Preta vary considerably in their distribution, morphology, and genesis. The classic black Terra Preta and associated midden debris represent household or near-household trash dumps (e.g., Birk et al., 2011; Schmidt, 2014), but the more ubiquitous dark brown *Terra Mulata*, largely devoid of artifacts or other obvious human debris, may

**Anthrosols, Figure 1** A Terra Preta soil of the Brazilian Amazon containing ceramic debris (Photo by William Woods).

represent agricultural soils modified by repeated mulching and frequent burning. This model of soil genesis has some important archaeological implications. It suggests long-standing habitation sustained by permanent gardens and fields. It also contradicts long-held models of settlement in the Amazon based on presumed agricultural limitations of upland and interior soils (see Denevan, 2001).

More broadly, the most widespread activity leading to development of anthrosols is agriculture (see entry on Soils, Agricultural in this volume). The development of agriculture probably has had more pervasive physical and chemical effects on soils than any other activity by preindustrial societies (Goudie, 2000, 29). Agriculture has imposed host of far-reaching effects on the landscape and on soils. The original plant cover can be partially or completely removed, leaving the ground bare for at least some part of the year and subject to erosion by water or wind. Cultivation loosens the soil and the hooves of domesticated animals can further loosen or compact it. Devegetation alters soil moisture and can affect groundwater. Plowing, excavation of irrigation ditches, and construction of terraced fields all physically disturb soils as well. Devegetation, new kinds of plant residues (from burning and cropping), and additions of fertilizer can all alter soil chemistry. Changes in groundwater conditions can drastically affect the soil forming environment. An elevated water table as well as irrigation also induces salinization if salts are present.

The unique morphological (macro- and micro-) and chemical characteristics of soils provide an excellent backdrop against which agricultural activities may be identified (Limbrey, 1975; Courty et al., 1989; Holliday, 2004). The physical signatures of agriculture in soils are related to the disruption of the lateral continuity of and vertical gradations between soil horizons. These disruptions result largely from plowing and the cutting of ditches and furrows. Probably the most obvious initial effect of farming is mixing of the upper solum by plowing. This process is widely recognized today in the identification of the "Ap" plowzone horizon.

At microscopic and chemical scales, impacts on soils due to human activity are generally much more subtle than physical impacts and usually require laboratory analyses for identification. Microscopically, the effects of agriculture include evidence for rapid infiltration of coarse-grained illuvial coatings from downward percolation of solutes or fine particles due to deforestation, and poorly-sorted mineral coatings and infillings of charcoal and SOM (soil organic matter; see below) due to farming.

Chemical impacts on soils come from human refuse and waste, burials, the products of animal husbandry in barns, pens, and on livestock paths, or intentional enrichment from soil fertilizer. With the advent of metallurgy and later industrialization, a much broader spectrum of chemicals and chemical compounds was added to the soil, such as heavy metals and hydrocarbons. The most common chemical elements added to soils by human activity are carbon, nitrogen, phosphorus, and calcium, with lesser amounts of potassium, magnesium, sulfur, copper, and zinc. The most common chemical compound added to soils by humans in agricultural and preagricultural societies and that is also easily recognizable in the field is soil organic matter (SOM). Human activity, largely through discard of organic waste (either in middens or as fertilizer), can add significant amounts of organic matter to the soil surface. Further, additional SOM can be produced and added to the soil by stimulation of soil biota and above-ground biomass subsequent to human activity due to more favorable nutrient conditions often associated with anthropogenic changes. These are notable characteristics of the anthrosols described below.

Anthropogenic additions of carbon, nitrogen, phosphorus, calcium, potassium, magnesium, and sulfur in theory can be used as indicators of past human activity. Most of these elements are removed from soil more or less readily by leaching, oxidation, reduction, or plant uptake, however (Eidt, 1977; Carr, 1982, 127–131), and the nature and rates of these losses from the soil are determined by local biological and pedological processes. Phosphorus in its common form as phosphate, however, is stable and generally immobile in soils and is thus a sensitive and persistent indicator of human activity. Among the elements left in the soil by humans, only P leaves a prolonged signature of its human origins because natural and anthropogenic P tend to be strongly fixed in soils. The sources of anthropogenic phosphorus include (1) human and animal waste; (2) refuse derived from bone, meat, fish, and plants; (3) burials; and (4) manure used as fertilizer (Provan, 1971; Proudfoot, 1976; Eidt, 1984, 29–30; Bethell and Máté, 1989). When people add P to the soil as organic products or inorganic compounds, the P quickly bonds with Fe, Al, or Ca ions (depending on local chemical conditions, particularly pH) to form relatively stable chemical compounds of inorganic phosphate minerals (Proudfoot, 1976; Bethell and Máté, 1989; Holliday and Gartner, 2007). In most soils, removal of these compounds cannot be stimulated by normal oxidation, reduction, or leaching processes, as is true of other elements (Proudfoot, 1976; Eidt, 1977, 1984, 1985). When humans add P to the soil, therefore, it accumulates at the site of deposition. With prolonged occupation, the accumulation of anthropogenic P can become quite large (by orders of magnitude) in comparison to the content of natural P in the soil. Other elements are cycled much more rapidly, assisted by microorganisms and plants in their cycling through the ecosystem, so the record of their association with people is lost.

Another factor which makes P suitable for geoarchaeological study is that anthropogenic P can exist in the pH range of most soils. Under acidic conditions, P combines with iron and aluminum, whereas under basic conditions, P combines with calcium. Consequently, soil P analysis can be used successfully in a wide variety of archaeological contexts. Indeed, where there is little or no surface evidence of human occupation, soil P analysis may be an appropriate tool for detecting traces of human activity and for determining the particular form and function associated with that presence.

The proportional relationships of certain ions have also been investigated archaeologically. Soil pH, which is an expression of the proportion of $H^+$ ions (or protons) to $OH^-$ (hydroxyl) ions, has some sensitivity to anthropogenic inputs. The concentration of cations (positively charged ions) in the soil strongly influences pH. Prolonged or more intense occupations tend to release more cations to the soil, and therefore, pH tends to be higher within deposits laid down under longer, denser, or more intensely occupied sites (Carr, 1982, 112).

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## Cross-references

Analysis of Carbon, Nitrogen, pH, Phosphorus, and Carbonates as Tools in Geoarchaeological Research
Dumps and Landfill
Shell Middens
Soils, Agricultural

# $^{40}$AR/$^{39}$AR AND K–AR GEOCHRONOLOGY

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## Synonyms

Ar–Ar dating; Argon–argon dating; K–Ar dating

## Definition

*K–Ar geochronology.* A geochronometer (geologic dating method) used to date potassium-bearing rocks, based on the decay of parent isotope $^{40}$K to daughter isotope $^{40}$Ar.

*$^{40}$Ar/$^{39}$Ar geochronology.* A variant of the K–Ar geochronometer, where $^{39}$Ar is measured as a proxy for the parent isotope $^{40}$K.

## Introduction

The K–Ar method and its derivative, the $^{40}$Ar/$^{39}$Ar method, are based on the radioactive decay of $^{40}$K to the noble gas $^{40}$Ar (sometimes symbolically indicated as $^{40}$Ar*, or radiogenic Ar). Potassium (K) is a major element in the Earth's crust and is abundant in many rocks and minerals. It possesses two stable isotopes: $^{39}$K (93 %) and $^{41}$K (7 %). After some early indications that a radioactive isotope of potassium of mass 40 might exist (for details see McDougall and Harrison, 1999, and references therein), it was definitively identified by Nier (1935). It was not until later that rocks enriched in $^{40}$Ar were identified and the first K–Ar ages produced on K-bearing feldspar and salt minerals (Aldrich and Nier, 1948). Evernden and Curtis (1965) presented the first application of the K–Ar method to constrain ages of paleoanthropological localities by dating rock layers, such as tephra and basalt at Olduvai Gorge, that lie stratigraphically above or below a significant archaeological deposit. Since then, K–Ar and $^{40}$Ar/$^{39}$Ar have been used to constrain the age of numerous paleoanthropological localities, including archaeological events as recent as the AD 79 eruption of Vesuvius that buried the Roman towns of Pompeii and Herculaneum (Renne et al., 1997).

Problematic issues with the K–Ar method (see below for details) were resolved with the introduction of neutron irradiation of samples prior to analysis (Merrihue and Turner, 1966). Irradiation converts some $^{39}$K to $^{39}$Ar, allowing for determination of parent and daughter isotopes using single samples and ultimately permitting single-crystal analyses. Early applications of the $^{40}$Ar/$^{39}$Ar method included efforts to constrain the age of the KBS Tuff in Koobi Fora, Kenya (Fitch and Miller, 1970; Fitch et al., 1974; Fitch et al., 1976; McDougall et al., 1980; McDougall, 1981).

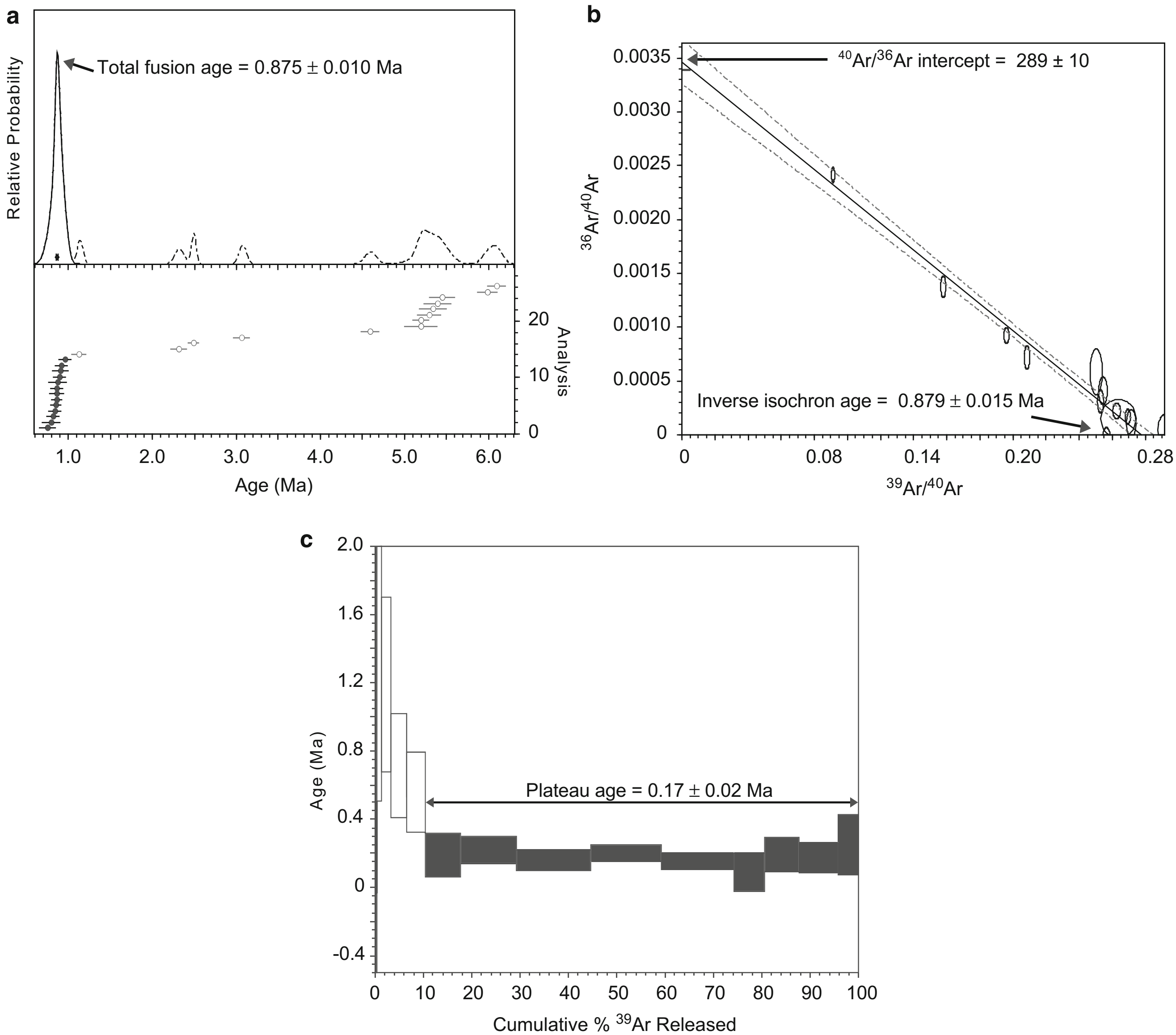
Today, $^{40}$Ar/$^{39}$Ar geochronology has largely superseded K–Ar and is applied to volcanic units at archaeological and paleontological sites globally. The method continues to play a key role in establishing timescales of human biological and behavioral evolution in regions with volcanic deposits.

## Principles of K–Ar and $^{40}$Ar/$^{39}$Ar geochronology

The K–Ar and related $^{40}$Ar/$^{39}$Ar methods are based on the constant rate of decay of $^{40}$K to $^{40}$Ar. A common measure of decay is the half-life, during which time half of the $^{40}$K atoms in a given system will decay. The $^{40}$K decay is a branched one, where about 90 % of atoms decay to $^{40}$Ca, while about 10 % of atoms transform into $^{40}$Ar. Application of these systems to archaeological environments is based on their ability to record the age of eruption for in situ volcanic rocks, which have been shown to be related in some way to archaeological remains, e.g., as a capping or underlying layer. Thus, the ages of crystallization for newly formed rocks or minerals are determined and used to bracket the dates of deposition for archaeological or paleoanthropological sites that are stratigraphically related.

The process often begins in a magma chamber within the Earth's crust, where K-bearing crystals of minerals such as feldspars, biotite, and hornblende form prior to eruption. At the high temperatures present in magma chambers, any $^{40}$Ar created by $^{40}$K decay within a crystal naturally diffuses out of the crystal. Upon eruption and subsequent cooling, argon diffusion is slowed so that any $^{40}$Ar created after the eruption is quantitatively retained within the crystal, thereby starting a radioactive "clock." By measuring the ratio of the "daughter" isotope ($^{40}$Ar) to the "parent" isotope ($^{40}$K), combined with values of the half-life for the branched decay of $^{40}$K, one can calculate the time that has passed since cooling. In the K–Ar method, assays must be conducted on two aliquots of the same sample, i.e., two crystals (or groups of crystals) from the same source: one to determine the amount of $^{40}$K and another to determine the amount of $^{40}$Ar.

The $^{40}$Ar/$^{39}$Ar method has ameliorated a number of issues involved with application of the K–Ar method, including that it allows for the measurement of K and Ar on a single-sample aliquot. This $^{40}$Ar/$^{39}$Ar variant relies on neutron irradiation of samples prior to analysis to




**$^{40}$Ar/$^{39}$Ar and K–Ar Geochronology, Figure 1** Examples of $^{40}$Ar/$^{39}$Ar data presentation. (**a**) Relative probability diagram for total fusion data from single crystal analyses. The youngest population, which is interpreted here to represent eruption age, is shown in black; xenocrystic contamination by older grains shown in gray (analytical data) and dashed lines (probability). Reproduced with permission from Morgan et al. (2012). (**b**) Same data as (**a**) graphed onto an inverse isochron diagram. The mixing line fit to the data indicates a trapped $^{40}$Ar/$^{36}$Ar component nearly indistinguishable from the atmospheric value of 298.56, and a radiogenic component with an age of ca. 879 ka. Reproduced with permission from Morgan et al. (2012). (**c**) Age spectrum from incremental heating data. Data from argon released during consecutive heating steps are shown from left to right. Note that consistent ages are identified over the last nine steps represented by the horizontal line; the weighted mean of these steps is presented as the plateau age (ca. 170 ka), which is read on the vertical axis. Earlier steps are inconsistent and omitted. Reproduced with permission from Morgan et al. (2009).

convert some fraction of the $^{39}$K present in the sample to $^{39}$Ar and therefore permit the measurement of $^{39}$Ar as a proxy for the parent isotope $^{40}$K. This is possible by using a natural value for the global $^{40}$K/$^{39}$K ratio (for purposes of most applications, this value is reasonably assumed to be constant).

A major advantage of the $^{40}$Ar/$^{39}$Ar system is that it allows for all required measurements to be made on a single-sample aliquot. Thus, analysis of single crystals becomes possible, permitting the identification of contamination from older, embedded crystals (or xenocrysts) that can be masked when using multigrain aliquots (Figure 1a).

In order to provide reliable ages, samples for $^{40}Ar/^{39}Ar$ analysis must be coirradiated with standards of a known age to determine the precise neutron flux of the reactor during irradiation. These standards may have been previously dated via K–Ar analyses (Lanphere and Dalrymple, 1966; McDougall and Roksandic, 1974; McDougall and Wellman, 2011) or based on intercalibration with other systems, such as the astronomical timescale (Kuiper et al., 2008) or the U–Pb geochronometer (Renne et al., 2010; Renne et al., 2011). The standard ages and decay constant values used to calculate $^{40}Ar/^{39}Ar$ ages have changed over time, typically as more precise and accurate values are determined. Understanding and comparing $^{40}Ar/^{39}Ar$ ages thus requires knowledge of the values used for their calculation.

When single grains are sufficiently large and/or old (thereby providing greater amounts of radiogenic $^{40}Ar$), the $^{40}Ar/^{39}Ar$ system can be further exploited by incrementally heating samples (rather than releasing all gas in a single, "total fusion" heating step). The "age spectrum" (Figure 1c) obtained by an incremental heating analysis can be used to identify problematic samples, assess the homogeneity of argon in crystals, and understand the thermal history of a sample.

Finally, when using the K–Ar method, one must make the assumption that argon trapped in the crystal upon cooling had an $^{40}Ar/^{36}Ar$ value equivalent to that of the present atmosphere. Most atmospheric argon is $^{40}Ar$ (99.6 %) and was produced by the decay of $^{40}K$, while argon in the solar system and beyond is largely $^{36}Ar$ (85 %), which is rare on Earth and forms a ratio of $^{40}Ar/^{36}Ar$ in Earth's atmosphere of 298.56:1 (Lee et al., 2006). This assumption can be tested using the $^{40}Ar/^{39}Ar$ method by viewing either total fusion or incremental heating data on an inverse isochron diagram (Figure 1b). This diagram shows the mixing between the trapped component $^{36}Ar/^{40}Ar$ (Y-intercept) and the radiogenic component $^{39}Ar/^{40}Ar$ (X-intercept). Deviations from an atmospheric trapped component, which are particularly important for young samples, can be identified and rectified.

## Sample materials

In archaeological settings, K–Ar and $^{40}Ar/^{39}Ar$ geochronology are often applied to various kinds of lavas and consolidated volcanic ashes, or tuffs. Within these materials, frequently analyzed potassium-bearing minerals include feldspars (particularly K-rich sanidine but also anorthoclase and plagioclase), biotite, and hornblende. Because of their young age, samples relevant to archaeological sites require higher potassium concentrations to obtain precise ages, so the utility of minerals with less K, such as plagioclase feldspars, is limited. For all samples, impurities such as fluid inclusions and alteration products should be avoided. For single-crystal work on young samples, desired grains are typically >250 μm. Although recent analytical improvements and optimum samples allow for analysis of grains as small as 50 μm, smaller grain sizes produce unreliable results due to nuclear effects during irradiation (Paine et al., 2006; Jourdan et al., 2007).

Analyses of lava flow samples can be conducted on mineral separates (e.g., one of the K-bearing minerals listed above), groundmass (microcrystalline matrix), or whole rock. Groundmass analyses require the separation of phenocrysts from a crushed sample, while in the case of whole rock, sample fragments are sufficient. Although care must be taken, some volcanic glasses such as obsidian can be a viable material for $^{40}Ar/^{39}Ar$ analyses, but glass shards from volcanic ashes have been shown to yield unreliable results that are difficult to recognize as inaccurate (Morgan et al., 2009).

The method can be applied to rocks as old as the Earth and, depending on their K content and required precision, as young as 1 ka. For example, basalts as young as 3 ka have been dated with precisions of 1 ka ($1\sigma$, here and throughout) (Hicks et al., 2012). Similarly, K-rich feldspars as young as the eruption of Vesuvius that destroyed Pompeii in AD 79 have been dated (accurately according to historical records) to $1.925 \pm 0.047$ ka (Renne et al., 1997). Precision typically degrades as signal size decreases (along with K content, age, and grain size), but it is important to distinguish analytical precision from accuracy, especially when comparing ages from different chronometers. Calibrations of standard ages and decay constants can result in total (analytical + systematic) uncertainties as low as <0.2 % at ca. 1 Ma (Renne et al., 2010; Renne et al., 2011), but perhaps more typical are uncertainties at the 1–2 % level (see case study below). However, recent calibrations of standard ages and decay constants do vary at the 0.3 % level in the same time frame (Kuiper et al., 2008; Renne et al., 2011) and are particularly important to consider when comparing ages obtained using different chronometers.

## Sampling procedures

Successful sampling for $^{40}Ar/^{39}Ar$ analyses requires careful preparation and implementation. Typical targets include volcanic ashes (e.g., tuffs) or lava flows that have been identified as having some relationship with the paleoanthropological material of interest. Accurate ages first and foremost require the careful documentation of stratigraphic and structural relationships between the dated unit and the horizons containing the archaeological evidence needing an age determination, as these field relationships ultimately control the significance of any obtained age constraints. Sampling volcanic ashes often requires care to avoid contamination from plant roots, both ancient and modern, which can rework sediments and introduce material of different ages into a sample. Success rates improve by examining a volcanic ash in a number of localities to identify the best one for sampling (i.e., the most crystal-rich and stratigraphically clear area). Lava flows can be variably altered, and success is improved by sampling the least altered regions.

## Laboratory procedures

The first step of sample processing involves separating K-bearing minerals from a bulk volcanic ash or lava sample by crushing (if the sample is indurated), sieving, and separation of minerals based on magnetic and density properties. Ultimately, individual grains are visually selected for further analysis; this can involve from tens to hundreds of grains per sample. Lava flows may alternately be run as “whole-rock” or “groundmass” aliquots, where either the entire crushed sample or the groundmass is selected for further analysis. Groundmass analyses require the removal of any phenocrysts present in the sample. Selected grains are often treated with hydrofluoric (HF) acid to remove alteration and weathering products as well as any remaining volcanic glass from grain surfaces. One exception to this is biotite, the argon systematics of which can be affected by acid treatment. Following these procedures, the samples are wrapped in aluminum packets along with appropriate standards and sealed in a quartz glass tube. Standards used should be of an age similar to that of the sample. For example, when dealing with quaternary samples, many workers use the 1.2 Ma Alder Creek sanidine standard (Nomade et al., 2005; Renne et al., 2011). Samples and standards are then sent for irradiation, where they are placed in the core of a nuclear reactor and thus experience a neutron flux. This induces the nuclear reaction $^{39}$K(n,p)$^{39}$Ar, in which a neutron is captured by the $^{39}$K atom and a proton is emitted, creating $^{39}$Ar. A number of other interfering reactions also occur, for which corrections must be made.

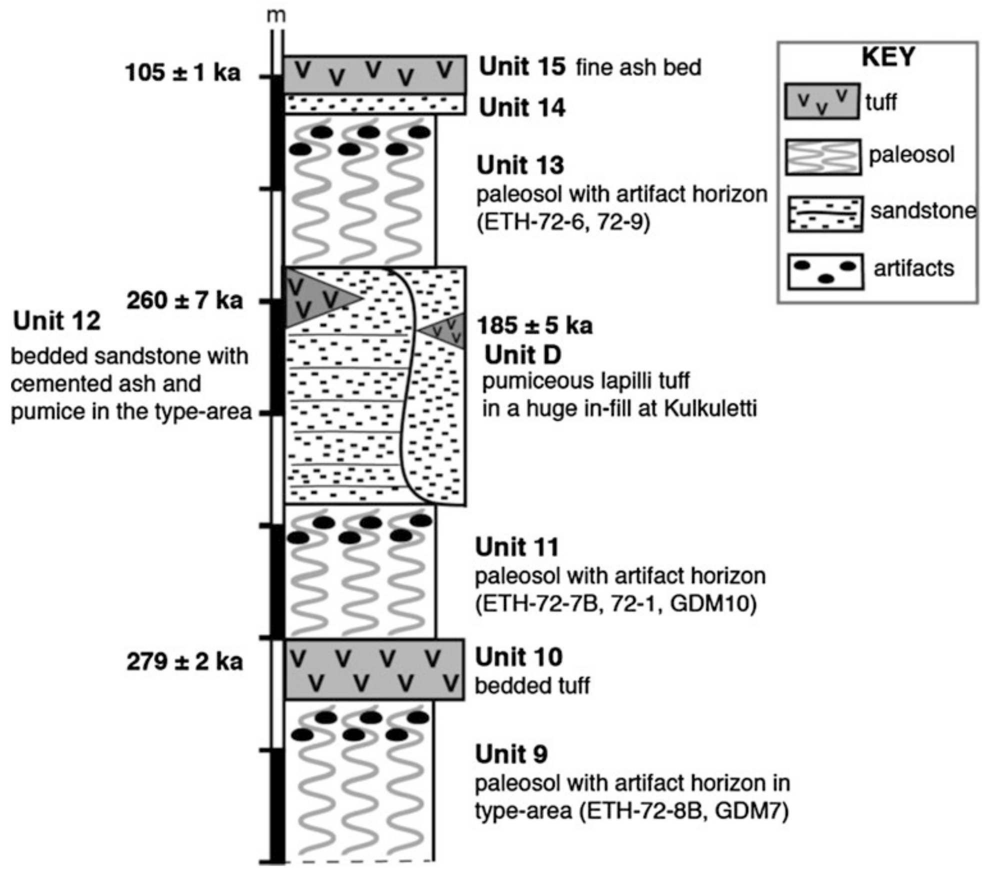
Following irradiation, samples and standard grains are transferred individually from irradiation packets into a disk for laser analyses (typically stainless steel or copper, with small pits for each grain), or foil packets for furnace analyses, which are loaded into the extraction line. The extraction line (which is directly connected to a noble gas mass spectrometer) is heated to ca. 100–150 °C under vacuum for at least several hours to decrease atmospheric argon contamination and reach pressure levels associated with an ultrahigh vacuum (ca. $10^{-9}$ mbar). Individual aliquots (typically single grains for volcanic ash samples) are then heated with a laser or furnace to release Ar from the grain. Laser analyses have lower “background” contamination than furnace analyses and thus are more commonly used for single-grain work.

The aim of total fusion analyses is to reach a temperature sufficient to release most Ar in a single step. Quantitative release of Ar is not necessary for age determinations. Incremental heating analyses (see above) begin at lower laser or furnace power; subsequent analyses increase that power sequentially. During and following heating (for either total fusion or incremental heating), released gas expands into an extraction line containing “getters” that trap reactive gases and thus serve to purify the noble gases (largely Ar) which do not react with getter material. Some laboratories also expose released gas to a “cryotrap,” which freezes out water and other condensable phases.

Purified gas is subsequently expanded into a mass spectrometer, where atoms are ionized via an electron impact source, accelerated through a flight tube, turned and separated according to isotopic mass by a magnet, and then detected. Recent advances allow for the simultaneous detection of multiple isotopes via multicollector detector arrays, though many systems still in use produce excellent data with single collectors by employing peak-hopping methods to measure each isotope multiple times. Between sample and standard analyses, system blank values are measured by reproducing all steps apart from powering the laser or furnace; values determined for each isotope are subtracted from each sample and standard analysis. A correction is also made for mass-dependent isotopic fractionation (or “discrimination”) in the mass spectrometer. This is achieved by comparing the difference between $^{40}$Ar/$^{36}$Ar values in an aliquot of cleaned natural air and the known $^{40}$Ar/$^{36}$Ar values of the terrestrial atmosphere, first estimated by Nier (1950) and updated by Lee et al. (2006). Although this is not always the case for historical ages, sufficient data should be published to allow for future age recalculation using different standard ages and half-life values. See Renne et al. (2009) for a complete description of reporting norms and requirements to allow for age recalculations using updated parameters.

## “Absolute” ages, uncertainties, and comparisons with other methods

Age interpretation from any chronometer often relies on the ability to associate or calibrate the system with other chronometers or calendar years. Although some chronometers conventionally calculate ages relative to a particular time (e.g., $^{14}$C), the K–Ar and $^{40}$Ar/$^{39}$Ar systems yield ages relative to the time of analysis. As discussed above, calibration is dependent on the half-life of $^{40}$K and standard ages applied to age calculations. Values for these parameters have been measured numerous times, and results can vary considerably between measurements (e.g., Beckinsale and Gale, 1969; McDougall and Roksandic, 1974; Steiger and Jäger, 1977; Renne et al., 1998; Min et al., 2000; Kuiper et al., 2008; Renne et al., 2010; McDougall and Wellman, 2011; Renne et al., 2011). Fortunately for paleoanthropological situations, relatively recent determinations (Kuiper et al., 2008; Renne et al., 2011) agree within 0.5 % of the age for relatively young samples (Renne, 2014), which is well within the geologic uncertainty (e.g., the association of dated material to the archaeological material) in most cases. Comparisons of legacy data with newer results, however, may require age recalculation to modern standard and decay constant values; this can be accomplished when sufficient analytical information has been provided.




**$^{40}$Ar/$^{39}$Ar and K–Ar Geochronology, Figure 2** Composite stratigraphic section for Gademotta and Kulkuletti, Ethiopia. The $^{40}$Ar/$^{39}$Ar method was used to constrain the ages of tephra from units 10, 12, and D. Artifacts found in Unit 9 are some of the oldest known Middle Stone Age artifacts in Africa. Reproduced with permission from Sahle et al. (2014).

## Case study

Some of the earliest evidence for Middle Stone Age (MSA) archaeology in Africa is found in the Gademotta Formation near Ziway, Ethiopia. First excavated and dated by K–Ar in the 1970s by Fred Wendorf and colleagues (Wendorf and Schild, 1974), the ages of sites in the type locality and the nearby Kulkuletti area were revisited using the $^{40}$Ar/$^{39}$Ar method in the 2000s (Morgan and Renne, 2008). Ages were obtained on sanidine crystals from two key tephras in the stratigraphy, Units 10 and D (Figure 2), and glass shard geochemistry linked the tephras between the two localities. The $^{40}$Ar/$^{39}$Ar method yielded ages even older than those from K–Ar, likely due to incomplete degassing of feldspars during the K–Ar analyses. Artifacts found below Unit 10 (279 ± 2 ka) indicate that Gademotta contains some of the earliest known MSA artifacts. Renewed interest in the site led to further excavations (Sahle et al., 2013; Sahle et al., 2014), in which additional $^{40}$Ar/$^{39}$Ar work yielded an age for a previously undated layer (Unit 12). Archaeological data indicate that the lowermost Gademotta site contains the earliest evidence for stone-tipped projectiles (Sahle et al., 2013).

## Summary

K–Ar and $^{40}$Ar/$^{39}$Ar geochronology exploit the decay of $^{40}$K to $^{40}$Ar. They have been used to constrain the ages of numerous paleoanthropological localities in areas with suitable volcanic deposits around the world. The age constraint is typically obtained for a volcanic rock interbedded or otherwise associated with archaeological and/or paleontological material, and thus the analyzed sample yields minimum or maximum ages for that material, depending on the association.

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## Cross-references


Isochron Dating
Pompeii and Herculaneum
Radiocarbon Dating
Tephrochronology
U-Series Dating

## ARCHAEOLOGICAL STRATIGRAPHY

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### Introduction

Archaeologists have utilized stratigraphy in order to correlate sediment layers and archaeological assemblages for well over a century (Harris, 1989; Lyman and O'Brien, 1999; O'Brien and Lyman, 1999; Stein, 2000; Mills and Vega-Centeno, 2005). Relative-age determination based on the law of superposition and context is now used in essentially all archaeological excavations, and it is the foundation of almost every other dating technique as well as being more frequently applied than any other method. A site may contain hundreds of superimposed sediment layers, or built structures such as plazas, foundation walls, and streets, but in every case, stratigraphy is needed to interpret the age relationships of the artifacts and architecture. Stratigraphy is also crucial in reconstructing the landscape of occupation and past environments and in understanding *site formation processes* (see entry on Site Formation Processes in this volume). There have been few attempts to establish a systematic approach to archaeological stratigraphy and a nomenclature for its concepts and terms, however.

In contrast, geologists have compiled stratigraphic guides in response to the need "for uniform standards and common procedures in defining and classifying formal rock bodies, their fossils, and the time spans represented by them" (North American Commission on Stratigraphic Nomenclature, 2005, 1555). In these guides, the language used to denote rock units and their spatial and temporal relations has been formalized. In most geological stratigraphic guides, subdivisions of rock sequences are based on lithology (*lithostratigraphic units*), on fossil content (*biostratigraphic units*), and on the time periods in which rocks were deposited (*chronostratigraphic units*). Stratigraphic classification also includes soils and related weathering phenomena (*soil-stratigraphic* or "*pedostratigraphic*" *units*) and bounding discontinuities (*allostratigraphic units*) (see entries on Stratigraphy and Soil Stratigraphy in this volume) (North American Commission on Stratigraphic Nomenclature, 1983, 2005).

To establish stratigraphic schemes at archaeological sites, some archaeologists and geoarchaeologists have simply followed the rules of the *Code of Stratigraphic Nomenclature* established by geologists (North American Commission on Stratigraphic Nomenclature, 1983, 2005) or the *International Stratigraphic Guide* (Hedberg, 1976; Salvador, 1994; Murphy and Salvador, 2000). This can work as far as the Code goes, but it was established by and for geologists working with bodies of rock and spans of time longer than would be encompassed by most archaeological sites. Further, some archaeological sites contain geologic or occupation records that are very complex within very small areas (e.g., a cave or a tell). In geology, local complexities can be subsumed within the characteristics of larger bodies of rock. In archaeology, the localized geologic complexities of sites may be of particular interest because they have a direct bearing on interpreting the occupation record and the site formation processes. For example, local spring deposits may hold a crucial component of the archaeological record in a larger site, and thus establishing a nomenclature for those spring deposits is essential. Typical for many site stratigraphies are simple letter or number sequences (e.g., strata 1, 2, 3 or units A, B, C) with subdivisions (e.g., 1A, 1B or A1, A2). Formation/member terminology, following the North American Commission on Stratigraphic Nomenclature, has been applied in a few geoarchaeological situations (e.g., Laury and Albritton, 1975; Stafford, 1981; Haynes and Huckell, 2007).

Following the example of geologists, some archaeologists and geoarchaeologists have proposed a set of rules for clarifying terminology and classification in archaeological stratigraphy. Schiffer (1972, 1976, 1983, 1987) proposed a classification scheme for the archaeological record based on objects found within deposits rather than on the physical characteristics of the deposits themselves. Harris (1977, 1979, 1989; Harris et al., 1993) made a significant contribution when he proposed a modest classification system, with special emphasis on how to record stratigraphy. The "Harris Matrix" may be the best known and most widely applied archaeological stratigraphic classification system, but it is best applied in sites with a complex history of occupation with numerous features and abundant artifacts (see also papers in Roskams, 2000).

Gasche and Tunca (1983) were the first to propose a formal archaeological stratigraphic nomenclature based on geological guides as well as three separate formal units for archaeological strata based on lithology, artifactual content, and time periods. The purpose of Gasche and Tunca's guide is to "facilitate and even to stimulate the exchange and correlation of all information produced from archaeological sites . . . and to establish a cross-referencing system, which would be as objective as possible . . . and that would eliminate the ambiguities brought about by an arbitrary language" (Gasche and Tunca, 1983, 325).

Gasche and Tunca proposed three stratigraphic units for dividing archaeological sediments: (1) on the basis of lithology, i.e., lithologic units; (2) on artifactual content,

**Archaeological Stratigraphy, Table 1** Formal stratigraphic terms used in geoarchaeology and geology

| Classificatory basis | Stratigraphic classification Geoarchaeology | Formal subdivisions | Stratigraphic classification Geology | Formal subdivisions |
|---|---|---|---|---|
| Lithology (physical and/or | chemical composition) | Lithologic unit<br>*Time-transgressive* | Layer<br>Sub-layer<br>Inclusion<br>Elemental sediment unit | Lithostratigraphic unit<br>*Time-transgressive* |
| Formation, member, bed | | | | |
| Time | Chronostratigraphic unit<br>*Specific time interval* | Set<br>Phase<br>Sub-phase | Geochronologic unit<br>*Specific time interval* | Eon, era, period, epoch, age |
| Fossils | Biostratigraphic unit<br>*Time-transgressive* | Biozone | Biostratigraphic unit<br>*Time-transgressive* | Biozone |
| Artifacts | Ethnostratigraphic unit<br>*Time-transgressive* | Zone<br>Supra-zone<br>Subzone | None | None |

i.e., ethnostratigraphic units; and (3) on time periods, i.e., chronostratigraphic units. They argued that archaeostratigraphy can be accommodated by two additions to existing geologic stratigraphic guides and codes: (1) a lower-ranking lithostratigraphic unit called the Layer that would include subdivisions of strata useful for archaeology and microstratigraphy and (2) ethnostratigraphic units called the Zone, Supra-zone, and Subzone that would divide sequences of layers according to their artifactual content. This scheme has not been widely adopted, but it provides a good starting point for a broader discussion of archaeological stratigraphy (Table 1).

## Lithologic units

A lithologic unit is a "three-dimensional body characterized by the general presence of a . . . (dominant) . . . lithologic type, or by the combination of two or more of these types, or even by the presence of other particularities that confer on the unit a homogeneous character. . .. Among other particularities, detailed attention should be paid to the lithologic content, the structure, texture, and color of the content, and the degree of erosion or denudation and their geometry" (Gasche and Tunca, 1983, 328, 329). In the archaeostratigraphic guide, the lithologic unit is equivalent to the *lithostratigraphic unit* in other geological stratigraphic guides and codes. Lithologic units are termed "Layers" (the basic unit used in stratigraphic correlations), "Sub-layers" (lithologic units that form part of a Layer), and "Inclusions" (smaller units that are part of a Layer or Sub-layer).

Although Gasche and Tunca (1983) were the first in archaeology to define a lithologic unit comprehensively, Fedele (1976, 1984) had suggested a similar unit earlier. Fedele defined an elemental sediment unit (ESU) as "a unit constituting the smallest geologically homogeneous entity as perceived in excavation . . . (and) contained between two consecutive recognizable discontinuities" (Fedele, 1976, 34). An ESU could be a stratigraphic division, a lateral (facies) differentiation, or a pedological horizon. An ESU is a ". . . formally named fact in the structure of a given site, whose mappable distribution can eventually be used as a marker" (Fedele, 1984, 11).

The proposal to adopt "lithologic unit" in geoarchaeology led to much discussion and some favorable reviews (Colcutt, 1987; Fedele and Franken, 1987; Farrand, 1984; Le Tensorer, 1984; Stein, 1987). The new unit was seen as needed due to (1) problems of scale; (2) disagreement as to the importance and nature of discontinuities in archaeological lithologic units, in contrast to the importance and nature of discontinuities in geological lithostratigraphic units; and (3) the need to describe archaeological sediments with attention to characteristics that are appropriate for archaeological stratigraphic inquiry. Stein (1990), however, argued that there was insufficient reason to propose a new type of lithostratigraphic unit. Rather, there was need for a formal lithostratigraphic unit (i.e., in the North American Commission on Stratigraphic Nomenclature) smaller than the existing unit of lowest rank (the Bed).

The first and most obvious dissimilarity between an archaeostratigraphic "Layer" and other lithostratigraphic units is in scale. The primary lithostratigraphic unit for geologists is the formation. Its spatial characteristics are purposely vague. The authors of the *International Stratigraphic Guide* say that "the thickness of units of formation rank follows no standard and may range from less than a meter to several thousand meters . . . [and that the] practicability of mapping and of delineation on cross sections is an important consideration in the establishment of formations" (Hedberg, 1976, 32). The authors of the *North American Stratigraphic Code* state that "thickness is not a determining parameter in dividing a rock succession into formations; the thickness of a formation may range from a feather edge at its depositional or erosional limit to thousands of meters elsewhere. . .. No formation is considered valid that cannot be delineated at the scale of geologic mapping practiced in the region where the formation is proposed" (North American Commission on Stratigraphic Nomenclature, 2005, 1569). Mappability is a crucial determinant in these two definitions. In archaeology, strata are differentiated in much the same way as in geology (i.e., on the basis of physical characteristics), but typically on the scale of a few meters down to centimeters or millimeters. Archaeological strata are also convenient for mapping at a scale appropriate for an archaeological site, but not always for a geologic region.

Layers that terminate laterally over short distances are common in archaeological sites (Tunca, 1987; de Meyer, 1984), and often they cannot be condensed into one general sequence (Cordy, 1987a). Correlations in stratigraphically complex archaeological sites frequently depend on the order of deposition of small disparate layers (discerned by recording overlapping edges) rather than on major stratigraphic units extending over the whole site. Thus, archaeologists do not expect to use "layers" in the same manner as geologists use "formations."

The importance and nature of discontinuities in archaeological stratigraphy generated some discussion, centering on an argument that discontinuities generated by humans are different from, and more numerous than, geologic discontinuities, and they therefore need their own terminology (Gasche and Tunca, 1983, 329). Logic argues that archaeological discontinuities should be described using a descriptive classification based on geologic terms (e.g., abrupt conformities, angular unconformities, disconformities).

Strata in archaeological contexts tend to be described in much the same way that sedimentologists describe sediments. Basic descriptors include grain size, grain shape, mineral composition, sedimentary structure, and color. Archaeologists have also examined distinctive attributes of cultural deposits to see if they are different from traditional sedimentological analyses. Schiffer (1987) proposed that, in addition to traditional sedimentological descriptions, certain attributes of artifacts are distinctive and diagnostic in the interpretation of cultural deposition (e.g., roundness of sherd edges). Stein and Teltser (1989) showed that grain-size distributions of separate compositional types of artifacts (e.g., ceramics, lithics, bone) provide a basis for interpretations of archaeological deposition (see also Fladmark, 1982; Rosen, 1986; Hull, 1987; Dunnell and Stein, 1989). Whether non-geological or cultural attributes are necessary in archaeological descriptions of sediment, a standardized, descriptive (nongenetic) terminology is necessary for the description of archaeological (and geological) stratigraphic relations.

An important similarity between the geoarchaeological lithologic unit and the geological lithostratigraphic unit is that they can be time-transgressive ("diachronic"), that is, the age of the upper or lower contacts, or both, is not necessarily the same everywhere. This can be due to varying rates and timing of sedimentation, localized erosion, or localized burial. The correlation of lithologic units does not mean that they are of the same age and, therefore, they may not contain archaeological materials or features of the same age.

## Ethnostratigraphic units

Gasche and Tunca (1983, 331) proposed the term "ethnostratigraphic unit" for deposits identified on the basis of their anthropic content (i.e., artifacts). The terms "Zone" (the basic unit), "Supra-zone" (contains one or more Zones), and "Subzone" (subdivision of a Zone) are subdivisions of ethnostratigraphic units. Like the fossils that define biostratigraphic units, the artifacts of ethnostratigraphic units must be only those artifacts whose age of manufacture or use is coeval with the age of deposition of the strata, that is, the artifacts must be products of cultural activities taking place contemporaneously with the deposition.

To determine that an object was made or used concurrently with deposition requires that the observer determine the artifact's age and compare that with the age of the depositional event. Identification of an object as contemporaneous with deposition is, of course, an interpretation and a fundamental issue in fieldwork. Thus, because the goal of stratigraphy is to provide a descriptive system, selection of artifacts whose age of manufacture is contemporaneous with deposition is problematic. Clearly, correct interpretation of an artifact assemblage as contemporary with deposition depends on the training of the person examining the artifacts.

Archaeological stratigraphers follow the example of the *International Guide* and the *North American Stratigraphic Code*, by dividing strata that contain artifacts as distinct stratigraphic units on a level with lithostratigraphic and biostratigraphic units (Cordy, 1987a; Cordy, 1987b; Gasche and Tunca, 1983; Le Tensorer, 1984; van der Plas, 1987). Biostratigraphy and lithostratigraphy are recognized as means of subdividing a sequence of rocks based on different kinds of data. Lithostratigraphic units are subdivisions of rock bodies based on lithologic attributes, while biostratigraphic units are subdivisions-based biological attributes. Ethnostratigraphic units, therefore, are subdivisions of archaeological sediments (essentially unconsolidated rock) based on artifactual attributes. Artifacts accepted as being relevant to ethnostratigraphic description derive from artifact typologies and archaeological theory.

Gasche and Tunca (1983, 331) suggested that descriptions of ethnostratigraphic units be based on artifact classes. Lithologic units are characterized by the classes of artifacts they contain and then are regrouped such that all layers with the same classes of artifacts form one ethnostratigraphic unit. Gasche and Tunca did not discuss necessary conditions for defining a class of artifacts, however. Cordy (1987a, 1987b, 31) suggested that the artifact content of units is not the material on which ethnostratigraphy should be described. He suggested that culture (*entité palethnologique*) is the appropriate basis for definition. Cultures are interpreted from artifact assemblages, but archaeologists do not agree whether this is really possible (Willey and Phillips, 1958; Clarke, 1968; Dunnell, 1982; Binford, 1983; Watson et al., 1984).

Using artifact classes provides a more objective means for identifying ethnostratigraphic units, but such classes are not always standardized in a way that makes correlation from site to site possible. Different archaeologists with different research objectives might describe artifacts in grossly different ways and would certainly argue over the appropriateness of any given class, making stratigraphic correlations across regions extremely challenging. As with biostratigraphy and lithostratigraphy, archaeology needs a formal description of artifacts (separate from the concept of types and classes) that is routinely made at every site. A basic set of descriptive attributes on which all archaeologists would agree would be difficult to select, however. Archaeologists have been arguing about artifact classification for decades (e.g., Krieger, 1944; Spaulding, 1953; Ford, 1954).

Archaeologists routinely define so-called cultural groups on the basis of artifact assemblages, however. These seem to be reasonable approaches to ethnostratigraphy whether or not these groupings truly represent discrete cultures. Examples include a wide variety of ceramic assemblages representing cultural-historical groups such as those in the southwestern USA (e.g., Hohokam). Lithic assemblages are widely used to classify and subdivide archaeological records such as Paleo-Indian in North America (and subgroups such as Folsom and Clovis) or Paleolithic or Stone Age in the Old World (including Lower, Middle, and Upper Paleolithic as well as further subgroups such as Acheulean or Gravettian). The assemblages include descriptions of length, width, and shape of lithics and the temper, paste, surface decorations, and shape of ceramics. Once the assemblages are described and established, sequences of deposits can be grouped and divided on the basis of the presence, absence, or abundance of artifacts with certain attributes.

According to the archaeostratigraphic guide, ethnostratigraphic units are defined by the presence of the classes of artifacts that they contain. The decision about which classes are to be used is problematic, but it is best decided by someone trained in the theory and methodology of archaeology. As long as stratigraphers recognize that a body of rock can be subdivided by various schemes of classification, each independent of one another and developed for specific needs, ethnostratigraphic units should be considered as valid stratigraphic units distinct from lithostratigraphic or biostratigraphic units.

The use of artifacts, as opposed to deposits, to establish stratigraphic sequences in archaeology permits interpretations of reversed stratigraphy, and primary and secondary deposits. When labeling a sequence as "reversed," archaeologists are referring to the temporal order of the age of manufacture for objects contained in the deposit. The terms "primary" and "secondary" deposits describe the history of individual objects within the deposit rather than the deposit itself. The concept of secondary deposit in archaeology refers to the source of the individual artifacts within the deposit. A deposit is considered secondary when at least one of the artifacts within it was transported from another location where it was part of a primary deposit.

Like the lithologic unit, ethnostratigraphic units cannot be assumed to be the same age everywhere. They can be time-transgressive. Artifact assemblages can appear later or last longer in some areas, but not others. Unfortunately, artifact or assemblage correlations are routinely used to make numerical age correlations. Artifact assemblages *generally* can be the same age from place to place, but the timing of their appearance or disappearance cannot be assumed.

## Chronostratigraphic units

"Chronostratigraphic units" are suggested as archaeological time-stratigraphic units that are characterized by their duration and by their temporal relations (Gasche and Tunca, 1983), similar to their use in formal geological stratigraphy. Chronostratigraphic units include one or several strata whose sedimentation took place during a specific time interval. The term "Phase" is proposed as the basic time unit. A phase is a grouping of adjacent strata of anthropic origins with a separate grouping of adjacent strata for those of natural origins. A "Set" is a group of phases, and a "Sub-phase" is a subdivision of a phase (1983, 330).

Gasche and Tunca (1983) only minimally discussed the chronostratigraphic unit, and they provided no valid arguments for accepting it as something different from geological chronostratigraphic units. Obviously, they considered the phase to be a subdivision of archaeological sediment that was deposited during a certain period of time, but they did not emphasize the difference (if any) between these sediments and geologic sediments. Rather than elaborate on the purpose of these units and how they differ from geological stratigraphy, Gasche and Tunca elaborated on the "constitution of chronostratigraphic units" (1983, 330). They detailed the manner in which a phase is to be grouped. They emphasized the need to separate deposits that have natural origins from those that have cultural origins and the need to distinguish from natural deposits those "... anthropic deposits whose sedimentation is caused by positive occupation by man (occupation of living floors) or negative occupation by man (filling, raising, etc.)" (p. 330). These preoccupations with natural versus cultural origins are another way of saying that they are subdividing the rocks by their artifact content or as ethnostratigraphic units. This perspective is an ethnocentric view of sedimentation, appropriate for creating ethnostratigraphic units, but it has nothing to do with chronostratigraphic units.

In both geology and archaeology, stratigraphers order strata in temporal sequences. In geology the temporal scale is often longer than in archaeology, but the difference is not sufficiently great to warrant, proposing a new time-stratigraphic unit. Lower-ranking time-stratigraphic units appropriate for archaeological stratigraphy are already inherent in the geologic stratigraphic codes. Both disciplines depend on superposition and isotopic dating to order strata, and both have problems with strata representing deposition that transgresses time (Watson and Wright, 1980).

Archaeological stratigraphy needs shorter but nevertheless formal time terms. In the Americas, for example, the Late Pleistocene and the Holocene, both formal components of the geologic time scale, encompass all of archaeological time; both terms are widely used, including subdivisions of the Holocene into Early, Middle, and Late. Formal definitions of those subdivisions were only recently proposed (Walker et al., 2012), however. In the Old World, chronostratigraphic subdivisions of the Pleistocene (Early, Middle, and Late) are widely used time terms and are well defined geologically (Gibbard and Cohen, 2008), but they span long temporal intervals.

With the advent of coring glaciers, shorter spans of time are being formalized for the Late Pleistocene. As formally defined, the Late Pleistocene began at the start of the last interglacial cycle ($\sim$130,000 years ago) and ended with the start of the Holocene. This interval encompassed a broad and complex array of behavioral and biological changes among hominins across Europe, Africa, and Asia, so chronostratigraphic subdivisions are useful. In the Americas, archaeological interest in the Late Pleistocene generally focuses on the final few millennia, so subdivisions are likewise useful. The Younger Dryas chronozone is a good example. Originally based on plant assemblages in northern Europe (a biostratigraphic unit), the term eventually became synonymous with a cold interval (a climatostratigraphic concept) in the last millennia of the Pleistocene. But plant assemblages and climate intervals are time-transgressive and not always globally synchronous nor even recognizable (Meltzer and Holliday, 2010). So now the Younger Dryas is most commonly intended as a time term (Björck, 2007) that is useful in both the Old and New Worlds.

Chronostratigraphic units in geoarchaeology, like their geologic equivalent, are not time-transgressive. Their upper and lower boundaries are the same age everywhere. For example, the lower boundary of the Holocene is about 10,000 radiocarbon years ago everywhere (Björck, 2007). Arguments over the age of the boundaries are normal and to be expected, but by definition they cannot be diachronic (shift around in time). The point of chronostratigraphic units is the designation of previously agreed-upon intervals of time. In our modern lives, each month has an agreed-upon beginning and end to serve our purposes of time keeping. If the beginning or end of chronostratigraphic units varied in time, the point of having such stratigraphic subdivisions would be defeated.

## Summary

Archaeologists recognize the need to minimize ambiguity and clarify the distinctions among different kinds of stratigraphic units. To this end, Gasche and Tunca (1983) proposed an archaeostratigraphic guide, which introduced stratigraphic units: lithologic, ethnostratigraphic, and chronostratigraphic. The history and viability of archaeostratigraphy and proposed stratigraphic units was further examined and discussed by Stein (1987, 1990, 2000).

Gasche and Tunca proposed the "lithologic unit," similar to the lithostratigraphic units of geologic stratigraphic codes and guides, but subdivided into subunits with rankings of "Layer," "Sub-layer," and "Inclusion." The only characteristic of these subunits, however, that is different from previously proposed geologic lithostratigraphic units is the inferred difference in scale. Rather than proposing an entirely new lithologic unit with three ranks, Stein (1990) proposed that "Layer" suffice as a single, smaller-ranking unit of geological lithostratigraphy.

The "chronostratigraphic unit" discussed in the proposed archaeostratigraphic guide is not sufficiently different from geologic chronostratigraphic units to be justified. For purposes of archaeology, the chronostratigraphic and geochronologic units proposed in the various geological stratigraphic codes are adequate. Chronology is important in both archaeology and geology, and although the intervals of time on which each discipline focuses vary, the differences do not warrant creating a new chronostratigraphic unit for use in archaeology.

The "ethnostratigraphic unit" is a valid unit in which stratigraphic classifications of strata are based on their artifactual content. As with biostratigraphic units, divisions of ethnostratigraphic units are based on their content. The ethnostratigraphic unit requires a separate name because it involves separate theoretical and taxonomic principles. Although archaeologists may not yet agree as to the standardized description of artifact classes, the division of sediment sequences according to the presence of various artifacts is a valid stratigraphic practice and deserves to be recognized. Archaeologists have long used what could be described as ethnostratigraphic unit in various cultural-historical constructs.

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## Cross-references

Chronostratigraphy
Climatostratigraphy
Harris Matrices and the Stratigraphic Record
Sedimentology
Site Formation Processes
Soil Stratigraphy
Stratigraphy

# ARCHAEOMAGNETIC DATING

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## Synonyms

Archaeointensity dating; Archaeomagnetism; Directional dating; Magnetic dating

## Definition

*Archaeomagnetism*. The study of the magnetic properties of archaeological materials.

*Archaeomagnetic dating*. The dating of archaeological materials that retain fossilized records of the Earth's magnetic field by comparing the direction and/or strength of the material's magnetism with known records of changes in the Earth's magnetic field through time.

*Geomagnetic secular variation*. Changes in the strength and direction of the Earth's magnetic field with periods of a year to millions of years (Merrill et al., 1998); not to be confused with polar reversals, which have periodicities of hundreds of thousands to millions of years.

## Introduction

At its root, archaeomagnetic dating grew out of the early observations that fired materials become magnetized parallel to the ambient magnetic field (Boyle, 1691; Gilbert, 1958) and that the geomagnetic field changes through time (Halley, 1692; see Tarling, 1983). More focused research in the late nineteenth and early twentieth centuries on the magnetization of baked clays and lava flows (Melloni, 1853; Folgheraiter, 1899; Mercanton, 1918; Chevallier, 1925) further refined and linked these observations, providing the foundation for modern paleomagnetic studies, including archaeomagnetism. As a discipline, archaeomagnetic studies were firmly established through the work conducted by Émile Thellier and his students between 1930 and 1960 (Thellier, 1936, 1938; Thellier and Thellier, 1959). During this period, these researchers explored and described the magnetic properties of baked clays, developed sampling techniques for recovering archaeomagnetic materials from the field, and designed and developed laboratory equipment and techniques for analyzing archaeomagnetic samples. By 1960, these methods had been greatly refined, and archaeomagnetic studies were undertaken in various parts of Europe (Cook and Belshé, 1958; Aitken, 1958), Japan (Watanabe, 1959), and the Soviet Union (Burlatskaya and Petrova, 1961). A few years later, the technique was introduced to archaeologists working in the American Southwest (Dubois and Watanabe, 1965), and by 1967 it was being used to date archaeological sites throughout that region (Weaver, 1967).

Today, archaeomagnetic dating is well established throughout Europe (Kovacheva et al., 1998; Le Goff et al., 2002; Schnepp and Lanos, 2005; Zananiri et al., 2007), the American Southwest (LaBelle and Eighmy, 1997; Lengyel, 2010), and parts of Mesoamerica (Wolfman, 1990; Hueda-Tanabe et al., 2004), and it is finding increasing success in areas such as the Middle East (Speranza et al., 2006), Northern Africa (Rimi et al., 2004), the American midcontinent (Lengyel, 2004), and parts of South America (Goguitchaichvili et al., 2011; Lengyel et al., 2011). Until recently, the majority of this work had been undertaken by paleomagnetists and geophysicists, who are primarily interested in using archaeomagnetic data to examine changes in the Earth's magnetic field over time. To a lesser extent, archaeological interest in the technique as an alternative dating method has either enabled or driven the development of the technique (Eighmy and Sternberg, 1990). New collaborations between these two groups of researchers – see, for example, the papers in Batt and Zananiri (2008) – have led to more synergistic approaches to archaeomagnetic dating.

## Archaeomagnetic principles

Archaeomagnetic dating depends on two related phenomena. First, the Earth's magnetic field changes in strength (intensity) and direction (inclination and declination) through time (i.e., geomagnetic secular variation), with significant changes occurring on the order of decades to centuries. Second, the soils that make up many archaeological features contain ferromagnetic minerals, such as hematite and magnetite, that can record the direction and strength of the geomagnetic field under certain conditions. By comparing the magnetization recorded by an archaeological feature to a calibrated record of secular variation, the age of the feature can be estimated. If the global geomagnetic field was produced by a simple geocentric dipole, similar to a bar magnet at the center of the Earth, it would be uniformly distributed, and a global model of geomagnetic field change through time could be used to determine when an archaeological feature was magnetized. However, only 80–90 % of the geomagnetic field at the Earth's surface can be ascribed to an inclined geocentric dipole. The remaining 10–20 % of the observed geomagnetic field is variably distributed across the global surface and concentrated primarily within six or seven continent-sized features that grow, shrink, and move through time. This is the non-dipole field, and it may add to, subtract from, or have no effect on the main dipole field in any given location. This heterogeneity of the non-dipole field necessitates the use of region-specific secular variation records for areas separated by several thousand kilometers. Thus, the age of magnetization can be ascertained only in areas for which this record has been established.

Typically, archaeological artifacts and features acquire a magnetization through heating. This thermoremanent magnetization (TRM) is acquired when archaeological materials are heated close to or above mineralogically specific temperatures (i.e., Curie temperatures; 580 °C for magnetite, 680 °C for hematite) and then cooled to ambient temperatures. As these materials cool below the Curie temperature, the ferromagnetic minerals will become magnetized parallel to the prevailing magnetic field. The material can retain this remanent magnetization unless it is reheated to a similar temperature, at which point a new magnetization will be acquired. Additionally, the material must remain stationary after magnetization in order to preserve the directional orientation (the declination and inclination) of the acquired remanence; the intensity of the remanence, however, is unaffected by physical movement. For this reason, archaeodirectional studies can be used to date stationary archaeological contexts only, such as fire pits, burned structures, or kilns, while archaeointensity studies can focus on portable objects, such as bricks and pottery, in addition to in situ archaeological features. It should be noted that archaeointensity tends to be less faithfully recorded than archaeodirection by some archaeological materials, and the identification of suitable materials is currently a hot topic in archaeointensity studies (Casas et al., 2005; Ben-Yosef et al., 2008; Shaar et al., 2010; Morales et al., 2011).

In some cases, anthropogenic water transport or containment features, such as canals or reservoirs, can acquire a depositional remanent magnetization (DRM) or postdepositional remanent magnetization (pDRM), which occurs when ferromagnetic grains physically rotate as they settle subaqueously during and/or after deposition to align with the geomagnetic field. As deposits accumulate, it becomes physically difficult for the grains that have been buried to continue rotating, and the magnetization acquired during or shortly after deposition becomes locked in. These types of features are encountered, and archaeomagnetically dated, much less frequently than thermal features (Eighmy and Howard, 1991).

For a more in-depth discussion of remanent magnetism and basic archaeomagnetic principles, see Tarling (1983), Butler (1992), and Merrill et al. (1998).

## Sampling methodologies

A variety of terminologies and sampling methodologies have been developed for recovering appropriate materials for archaeomagnetic dating (see Lanos et al., 2005; Trapanese et al., 2008). In all cases, the sampled material relates to a specific archaeological context that is assumed to have been homogeneously magnetized during a single event. For some researchers in the USA, the context is referred to as a feature, and the recovered material is referred to as a single archaeomagnetic sample, which is composed of multiple specimens. In most other regions, the context is referred to as a site from which multiple samples are recovered. In all cases, successful sampling begins with the identification of appropriate contexts for dating, taking into consideration the extent of firing (or deposition), the inclusion of appropriate ferromagnetic minerals, the size and preservation of the context, and, for directional studies, the integrity of the context (see Eighmy, 1990, for a thorough discussion).

For directional studies, sampling methods have been designed to remove individual pieces of material in such a way as to preserve the in situ orientation of the magnetized grains. Typically, between 6 and 20 oriented samples are recovered from a single context, providing a statistically valid dataset for the feature that can be used to calculate the mean direction of the magnetic remanence. This sample size has also been shown to minimize the effects of magnetic noise and random errors on the averaging statistics (Tarling and Dobson, 1995). In many cases, collectors employ some version of the original technique developed by Thellier (1967), which involves isolating material for recovery, with or without the use of square molds, encasing the material in nonmagnetic plaster or plastered bandages (Schnepp et al., 2008), marking the sample orientation on the plaster, and then removing the samples to the lab for further consolidation and subsampling. Typically, subsampling involves cutting anywhere from 1 to 20 cubic specimens (~4–27 $cm^3$) from each of the oriented samples (Kovacheva and Toshkov, 1994; Schnepp et al., 2004). In the USA, separate specimens are oriented and collected in the field, and the roughly 15 $cm^3$ specimens arrive in the laboratory ready for analysis (Eighmy, 1990). In the UK, collectors typically glue 2.5 cm plastic disks, leveled with a spirit level, to the flattened surface of well-consolidated material, mark the sample orientation on the disk, and then remove the disk with attached material to the lab for analysis. For less consolidated materials, these collectors push small plastic tubes (2.5 cm in diameter) into the material, mark the orientation, and then remove and seal the tubes before transporting them to the lab (Clark et al., 1988; Linford, 2006). For very hard materials, such as bricks or extremely well-fired kiln floors, samples can be removed with the standard water-cooled drilling method employed by most paleomagnetists (Collinson, 1983; Butler, 1992). In all cases, samples are oriented prior to removal, typically with a magnetic compass or a sun compass.

Archaeointensity sampling is less complicated and typically proceeds much more quickly, since the samples do not need to be oriented. Prepared specimens may be similar in size and shape to those collected for archaeodirectional analysis, or they may be smaller ~1 $cm^3$ microsamples (Donadini et al., 2008).

## Laboratory procedures

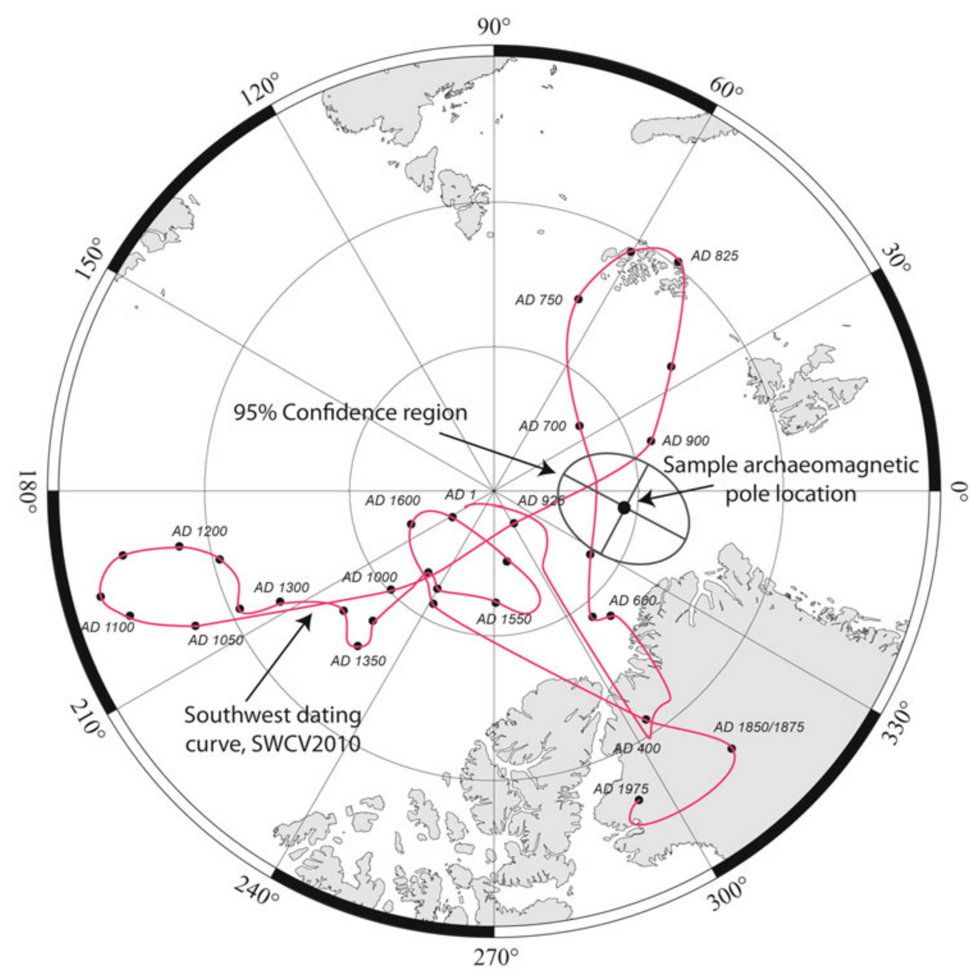
Archaeomagnetic laboratories have developed a number of techniques for isolating and measuring the characteristic remanent magnetization (ChRM) that is carried by archaeomagnetic samples. This is the primary magnetization that was acquired during the heating or depositional event of interest, and it is the information that must be retrieved in order to date the archaeological context. Over time, primary magnetization is overprinted with weaker and/or unstable secondary magnetic components that must be removed before the sample's ChRM can be determined. Typically, this is achieved by subjecting the individual specimens to sinusoidally decaying, weak alternating magnetic fields (AF demagnetization) or heating to low temperatures and then cooling within a zero magnetic field (thermal demagnetization). Both of these techniques have the effect of randomizing the magnetization of weak or unstable magnetic grains, effectively zeroing their contribution to the sample's overall magnetization. Most laboratories will measure the specimens prior to demagnetization in order to establish their baseline magnetization or natural remanent magnetization (NRM). Measurement is done with either a spinner or cryogenic magnetometer. Once the NRM is established, the demagnetization experiment begins by subjecting the specimen to low-level alternating fields, typically on the order to 5–10 mT (millitesla), or heating it to 50–100 °C. The specimen is then remeasured in the magnetometer, before being demagnetized at a higher temperature or peak field strength. Typically, labs will progressively demagnetize and remeasure specimens over a sequence of increasing temperatures or peak field strengths until the secondary components are removed. The changes in strength and direction that are measured over the course of demagnetization are statistically analyzed using principal component analysis (Kirschvink, 1980) to determine the specimen's primary direction of magnetization. Specimens that exhibit too much variation over the course of demagnetization are considered unstable and are excluded from further statistical analysis. Once the ChRM has been determined for each specimen, the results from all specimens are statistically averaged (Fisher, 1953) to calculate the mean direction of magnetic remanence, and associated error, for the sample. These values are then used to date the associated feature (see below).

Until recently, most labs routinely measured only the direction of the acquired magnetic remanence, due to the difficulties in reliably determining archaeointensities. However, the potential value of archaeointensity determinations, both for paleomagnetic field investigations (e.g., global field reconstructions) and archaeomagnetic dating purposes, has led several researchers to focus on improving the procedures used to determine these values (Le Goff and Gallet, 2004; Chauvin et al., 2005; Donadini et al., 2007, 2008; Ben-Yosef et al., 2008; Shaar et al., 2010). In theory, the strength of a sample's TRM (J) will be linearly proportional to the strength of the ancient geomagnetic field (H) that was present during cooling, such that $H = J/\chi_{TRM}$, where $\chi_{TRM}$ is a proportionality constant that indicates the material's susceptibility to TRM acquisition. Thus, by measuring the sample's intensity and then determining its proportionality constant by heating and cooling it within a known magnetic field, the intensity of the ancient geomagnetic field could be calculated. This straightforward approach presumes, however, that the sample retains a single magnetic component and that the magnetic mineralogy has remained unaltered since initial TRM acquisition, conditions that are rarely met in practice. Therefore, a much more complicated and time-consuming experiment is needed to establish the proportionality constant and estimate the paleointensity of the ancient field. Typically, researchers employ some form of the original experiment designed by Thellier (1938) and Thellier and Thellier (1959), in which individual specimens are repeatedly heated and cooled within a known field at increasing temperature intervals, twice at each temperature, in order to determine the range of temperatures over which the proportionality ratio remains constant. A variety of checks are employed throughout the experiment to monitor for laboratory-induced thermochemical alterations as well as the effects of nonideal magnetic grain sizes, cooling rates, and anisotropy of the specimen material (see Donadini et al., 2007). The experiment is repeated for all specimens in a sample, and a mean archaeointensity is calculated for the sample from a subset yielding statistically consistent results.

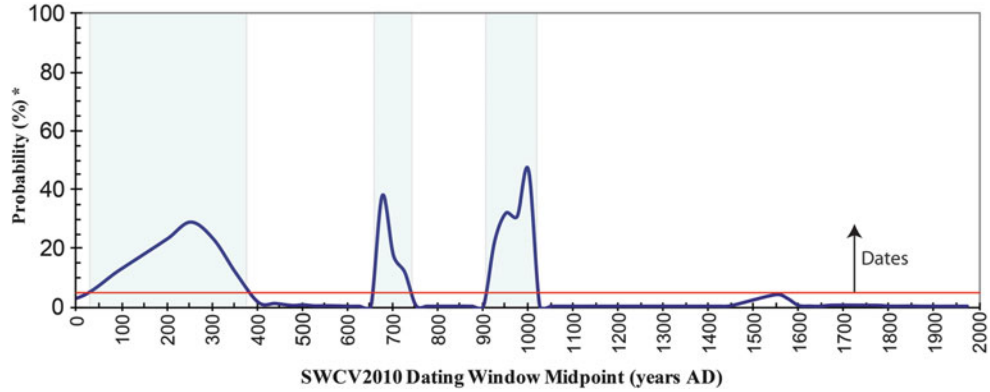
## Secular variation curves

Archaeomagnetic data obtained from an archaeological feature can be used to estimate that feature's calendrical age by comparing the data to a calibrated reconstruction of secular variation, often referred to as an archaeomagnetic reference curve. The reference curve can be depicted either as changes in inclination (I), declination (D), and, if available, paleointensity through time (Schnepp and Lanos, 2005; Zananiri et al., 2007) or as changes in the location of the virtual geomagnetic pole through time (Lengyel, 2010). Because secular variation changes randomly and the geomagnetic pole appears to "wander" spatially over time, reference curves are created from sources such as historically recorded direct observations of the field (Barraclough, 1994; Jackson et al., 2000; Korte et al., 2009), archaeomagnetic measurements of independently dated archaeological features (LaBelle and Eighmy, 1997; Zananiri et al., 2007; Valet et al., 2008), paleomagnetic measurements of dated sediment deposits (Nilsson et al., 2010) or lava flows (Hagstrum and Champion, 2002), or some combination of the above (Lengyel, 2004; Finlay, 2008; Hagstrum and Blinman, 2010). Archaeomagnetic or paleomagnetic data included in these datasets must be dated independently through other techniques, such as dendrochronology or radiocarbon dating, and precision criteria often require these data to have independent date ranges of 200 years or less (e.g., LaBelle and Eighmy, 1997: 432).

Furthermore, these curves can be calculated from either a regional dataset (Zananiri et al., 2007) or directly from a global model (Lodge and Holme, 2009). Curves that are based on regional datasets are typically calculated by smoothing archaeomagnetic data from within a 1,000 km area through some form of running average (Sternberg and McGuire, 1990; Le Goff et al., 2002) or within a Bayesian statistical framework (Lanos et al., 2005). Each of these methods utilizes some form of the conversion-via-pole method (Noel and Batt, 1990), which allows researchers to relocate archaeomagnetic data recovered from localities scattered across a region to a single reference location, such as London in the UK or Paris in France. This is done for each pair of measured declination and inclination values by first calculating the virtual geomagnetic pole for that pair of values at the respective sampling site and then calculating the subsequent declination and inclination values for that same virtual geomagnetic pole from the reference locality. In some studies, particularly those in the USA, the regional archaeomagnetic data are simply converted to virtual geomagnetic poles, and subsequent calculations use these pole positions rather than the converted declination and inclination data. It has been shown, however, that the relocation of data to a central location introduces potentially significant geographic error (Casas and Incoronato, 2007). As has been demonstrated recently, this error can be avoided by calculating local reference curves directly from global models, a method that has the added benefit of producing reference curves for specific locations, such as an archaeological site (Lodge and Holme, 2009). Because data coverage varies between global models, it




**Archaeomagnetic Dating, Figure 1** Archaeomagnetic sample data plotted against the American Southwest reference curve SWCV2010. This figure illustrates the regional secular variation curve for the American Southwest between AD 1 and AD 2000, and it depicts the virtual locations of the geomagnetic pole over that interval. Note the prominent loops in the curve at roughly AD 400, AD 825, AD 1125, and AD 1550. The sample data plots near a crossover in the curve at roughly AD 675 and AD 910, thereby intersecting more than one segment of the curve. This is a common situation in archaeomagnetic dating and results in more than one possible date range for the archaeomagnetic sample. Unlike radiocarbon date calibration, each archaeomagnetic date range obtained from the reference curve constitutes a unique 95 % probability range for that sample. Typically, other sources of chronometric data are consulted to determine which archaeomagnetic date range provides the best age estimate for the sampled archaeological context.




**Archaeomagnetic Dating, Figure 2** Mathematically derived 95 percent probability curve for the archaeomagnetic sample data plotted in Fig. 1 when compared to the SWCV2010 reference curve data via Sternberg and McGuire's (1990) statistical method. Spikes in the probability curve above the 5 percent significance line indicate time periods during which there is no statistically measureable difference between the sample data and the curve data. In other words, these are the time periods during which the sample data is said to "date" against the reference curve. Each spike constitutes an individual 95 percent date range for the respective sample.

may be less robust for some areas and/or time periods than is currently available through regional datasets, limiting the application of this method.

## Dating methodologies

The creation of archaeomagnetic reference curves and the dating of archaeomagnetic samples both rely on the underlying principle that archaeomagnetic materials that are the same age should exhibit similar geomagnetic characteristics. Thus, the data obtained from an archaeomagnetic sample can be compared to those of a calibrated reference curve for the region in question in order to ascertain the time periods during which both exhibit the same directional and/or intensity characteristics (Figure 1). This can be done visually or mathematically. The visual method is intuitively obvious and involves plotting the sample data and confidence limits against the regional reference curve. Visual inspection reveals the time period(s) during which the sample data were most similar to the magnetic field location and/or intensity, indicating the best-fit date range(s) for the associated archaeological feature. A greater variety of mathematical methods is available for estimating a sample's date range (Sternberg and McGuire, 1990; Le Goff et al., 2002; Lanos, 2004; Pavón-Carrasco et al., 2011; e.g., Figure 2), and in most cases these methods are preferred over the visual one due to their greater objectivity and the replicability of their results. However, the use of these methods is dependent on the availability of appropriately constructed reference curves with associated measures of uncertainty. Regardless which method is used, multiple dating solutions are often obtained because the path of secular variation loops back on itself through time, making it likely that sample data will match more than one segment of the reference curve. The use of the full magnetic vector for dating (i.e., both directional and intensity data) can alleviate this ambiguity, but the relatively limited spatial and temporal coverage of intensity curves currently restricts this approach to regions such as Central Europe (e.g., Kostadinova and Kovacheva, 2008). In most regions, researchers are advised simply to select the most likely dating option based on other archaeological evidence from the site.

Because archaeomagnetic data can be related directly to specific anthropogenic events, they lend themselves to addressing interesting archaeological dating questions. Typically, archaeomagnetic data are used to assess the age of individual archaeological features, such as kilns, furnaces, ovens, and hearths (Zhaoqin and Noel, 1989; Riisager et al., 2003; Jordanova et al., 2004; Casas et al., 2007), which have acquired the observed magnetic remanence during normal use. In some cases, archaeomagnetic data may provide one of the few methods for dating a specific context, such as unfired lime-plaster surfaces (Hueda-Tanabe et al., 2004) or hematite-pigment-painted murals (Zanella et al., 2000). Furthermore, archaeomagnetic data are especially well suited for reconstructing the use history of complex thermal sites such as glass-making installations (Linford and Welch, 2004), metallurgical workshops (Hus et al., 2004), and ceramic potteries (Kovacheva et al., 2004; De Marco et al., 2008), for which data from multiple features can be obtained and compared. Likewise, archaeomagnetic data recovered from multiple features at a single site can be used to resolve questions about a site's stratigraphy (Jordanova et al., 2004) or to address complex questions of site use through time (Donadini et al., 2012). In the American Southwest, in particular, it is not uncommon for extremely large suites of archaeomagnetic data to be recovered from numerous features ($N > 25$) across a single site for the express purpose of reconstructing the use history of the site, including the identification of different periods of occupation within a site's history and the ability to relate contemporaneous features across a large site (Sternberg et al., 1991; Chenault and Ahlstrom, 1993; Eighmy and Mitchell, 1994; Henderson, 2001; Deaver and Whittlesey, 2004; Lengyel, 2011). Finally, at even greater scales, archaeomagnetic data recovered from across archaeological culture areas may be used to assess and constrain cultural chronologies and the timing of archaeological phases within those chronologies. This has been particularly useful in the American Southwest, where archaeomagnetic data have played a key role in defining the Hohokam cultural chronology (Dean, 1991).

## Summary

Archaeomagnetic dating uses changes in the Earth's magnetic field through time to date archaeological contexts such as kilns, fire pits, and canals. These contexts acquire a remanent magnetization parallel to the ambient geomagnetic field under conditions such as firing to relatively high temperatures or fluvial deposition, and the magnetization is retained unless the material is reheated or disturbed. The context is dated by comparing its remanent magnetization to a calibrated record of geomagnetic secular variation, using the principle that contemporary archaeomagnetic materials will share similar geomagnetic characteristics. Until recently, researchers typically used only the directional component of the remanent magnetization to date archaeological contexts. However, renewed recognition of the value of utilizing the full vector for dating, as well as for geomagnetic field reconstructions, has prompted several researchers to focus on improving the methodology used to determine paleointensity values and to advocate for expanding the spatial and temporal coverage of paleointensity records.

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## Cross-references

Geophysics
Magnetometry for Archaeology
Paleomagnetism

## ARCHAEOMINERALOGY

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The term archaeomineralogy is relatively new. It was used by Mitchell (1985) for a brief bibliography, by Rapp (2002, 2009) for books, and by Kostov et al.,

(2008) and Rapp (2008) as part of the first international meeting on archaeomineralogy. This subdiscipline is quite distinct from the history of mineralogy. Archaeomineralogy is a subdiscipline of archaeology or geoarchaeology. It is the study of the exploitation of rocks and minerals by humans since prehistoric times for implements, ornaments, building materials, paints, and as raw material for metals, ceramics, and other processed products. Archaeomineralogy attempts to date, source, and characterize artifacts made from earth materials as well as put this information into geographic and historical contexts.

Scholars who could be called archaeomineralogists go back to ancient times and were located around the globe. Among the most prominent were the Hellenistic Greek philosopher Theophrastus (ca. 372–287 BCE), the Greek physician Dioscorides (ca. 40–90 CE), the Italian Pliny the Elder (ca. 23–79 CE), the Spaniard Isidore of Seville (ca. 560–636 CE), the Arab authors Al-Biruni (973–1048) and Avicenna (980–1037), the Chinese writer Su Song (1070), the Italian Albertus Magnus (ca. 1206–1280), and the German Georgius Agricola (1494–1555); various Sanskrit texts from India mention the use of a wide variety of minerals in medicine (Rapp, 2009).

The early Egyptians had one of the best understandings of mineralogy and lithology in the practice of medicine and the manufacture of monuments and ornaments (Lucas, 1989). Rock names such as basalt, syenite, porphyry, and alabaster have their origins in ancient Egypt. The igneous rock “basalt” appears to have the oldest roots, in use as early as 2000 BCE. The ancient Mesopotamians also had a well-developed understanding of rocks and minerals in industrial uses (Morrey, 1985).

In ancient times color was the most important character to classify rocks and minerals. Colors had significant symbolic attributes (mourning, purity, passion, danger) and minerals and rocks had medicinal and magic properties. Alchemists equated color with the essence or true nature of a substance. Modern understanding of the physical and chemical nature of mineral properties was established only in the early years of the nineteenth century by Joseph-Louis Proust’s Law of Constant Composition in 1799 and John Dalton’s Atomic Theory in 1805, and the development of accurate methods of chemical analysis.

It should be noted that early rock and mineral identification frequently was haphazard, often relying on color alone. The names given to many mineral species have changed over time and even today some minerals have a variety of names and synonyms (de Fourestier, 1999). Although there are more than a thousand names given to rock lithologies, sorting out what rocks were exploited in antiquity is somewhat easier than for minerals. An excellent guide to rock names is the “Glossary of Geology” (Neuendorf et al., 2005). This glossary presents historical definitions and obsolete variations in names and meanings.

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## Cross-references

Lithics
Pigments

# ARCHAEOSEISMOLOGY

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## Synonyms

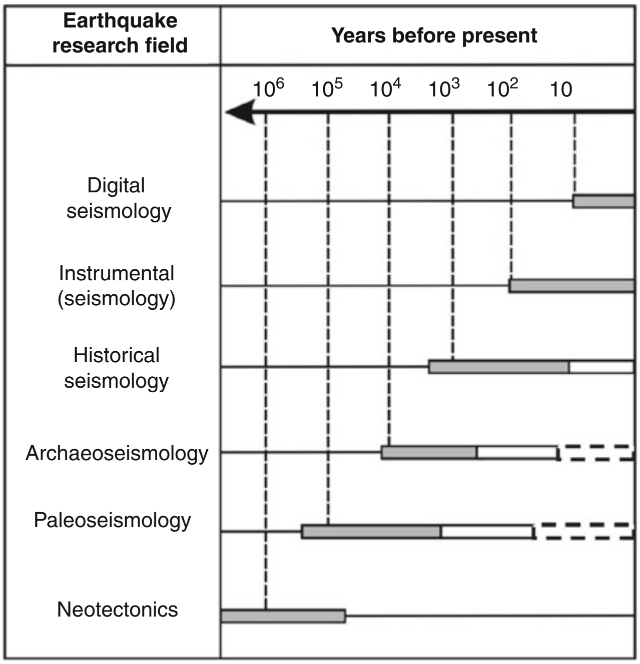
Earthquake archaeology; Seismic archaeology

## Definition

The study of ancient earthquakes at archaeological sites.

## Introduction

Earthquakes have disrupted human societies throughout history and prehistory. Whereas hunter-gatherer cultures may have been relatively little affected by seismic events, the built environment of sedentary societies can be quite vulnerable to collapse of structures by earthquake-induced ground motion. Understanding the severity and frequency of past earthquakes is important for understanding the history, consequences, and responses of past societies to these seismic disasters, as well as the hazards posed to modern populations. In many parts of the world, the recurrence of earthquakes is so infrequent that modern instrumental seismic data do not adequately represent the




**Archaeoseismology, Figure 1** The study of instrumentally recorded earthquakes is the field of seismology. Pre-instrumental earthquakes are studied by other methods, including historical seismology that encompasses written history, archaeoseismology that documents earthquakes at archaeological sites, and the geologic studies of paleoseismology and neotectonics (Modified after Caputo and Helly, 2008).

earthquake potential. Therefore, other methods to document the history of earthquakes are needed.

Various sources of data provide evidence of earthquake occurrence and magnitude, albeit at varying resolutions and over different time scales. Seismology, or the study of earthquake data recorded on analog seismographs, and now digital seismometers, is a field that has documented the date, time, and other parameters of seismic events over the past century or so. Information on earthquakes prior to the late nineteenth century relies on other research fields, including historical seismology, archaeoseismology, paleoseismology, and neotectonics (Figure 1). The figure clearly shows that the time domain for each field of earthquake study overlaps, often significantly. In historical seismology, the record of written history varies across geographic regions, and only a few cultures in the Near and Far East have produced written accounts of earthquakes that extend as far back as two to four millennia. Furthermore, historical texts become increasingly incomplete with increasing antiquity, as well as in regions of sparse population or discontinuous habitation. In many areas, historical records are completely absent. The physical remains of complex societies extend thousands of years farther back in time, well beyond the earliest historical accounts, and they are distributed more widely over the globe. Thus, the evidence of earthquakes at archaeological sites revealed by archaeoseismology may potentially fill a much-needed void in the record of seismic events. Geologists have also studied faults, deformation, and ground rupture from modern, historical, and ancient earthquakes within the well-established fields of paleoseismology and neotectonics.

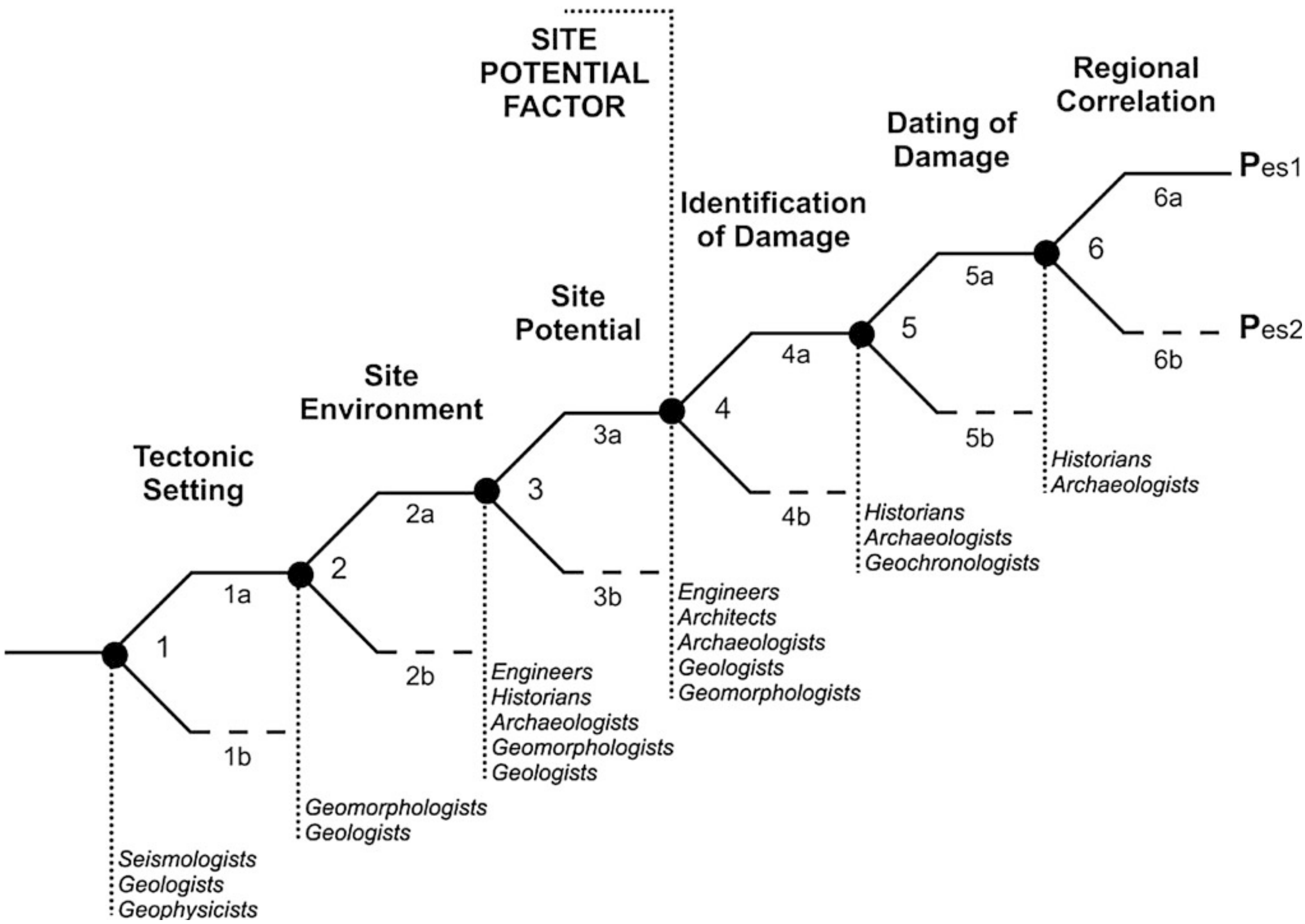
## History of the field of archaeoseismology

Ambraseys (1971, 1973) was one of the first to advocate the modern use of archaeological data to help define a region's earthquake history and other seismic hazards. Deciphering and dating evidence of earthquake damage at archaeological sites is the goal of the modern field of "archaeoseismology" – a term first coined in the paper by Karcz and Kafri (1978). Several other terms have been used for this emerging field, including "seismic archaeology" (e.g., Guidoboni, 1996) and "earthquake archaeology" (e.g., Sbeinati et al., 2010).

Many archaeologists have documented "destruction horizons," i.e., stratigraphic layers that show signs of fire, instantaneous destruction, or massive structural collapse with evidence of smashed, in situ vessels on living surfaces, toppled masonry, or other catastrophic building failures. These destruction horizons have been interpreted as evidence for ancient earthquakes since the late 1890s and early 1900s, when large-scale excavations of sites across the Mediterranean and Near East were launched (e.g., Arthur Evans's excavations of the Minoan palace at Knossos on Crete). While outlining the clear benefits of archaeological data in earthquake research, Ambraseys (1971, 1973) also cautioned that modern structures respond differently from ancient buildings to ground shaking. Because some ancient structures are still standing, it should not be concluded that the hazard of future earthquakes is low. Further, he observed that earthquakes should not be indiscriminately used to explain a sudden abandonment or large changes in cultural history.

The field of archaeoseismology investigates both earthquake collapse horizons within archaeological stratigraphic contexts and damaged extant buildings and structures. Earthquake damage is, however, difficult to differentiate from other causes of building failures, including static collapse due to lack of maintenance and disrepair, slumping or gravitational sliding, foundation subsidence, and other geotechnical issues (e.g., Karcz and Kafri, 1978; Rapp, 1986; Stiros and Jones, 1996; Galadini et al., 2006; Marco, 2008). Buildings and monuments damaged in an ancient earthquake may also show signs of repair. But again, many authors have noted that reconstruction phases may relate to expansion due to population growth repairs after military conflict, or political, social, or religious reorganization (e.g., Guidoboni and Ebel, 2009), and they cannot be strictly interpreted as evidence for an earthquake.

Archaeological excavations have traditionally concentrated on monumental structures and cities. Therefore,




**Archaeoseismology, Figure 2** Archaeoseismic quality factor (AQF) is a two-branch logic tree that can be utilized to evaluate whether an archaeological site is favorably located to record earthquake damage (site potential factor) and the extent to which features can be used as evidence for an earthquake based on the type of damage, its dating, and regional distribution (After Sintubin and Stewart, 2008).

the so-called hinterland or rural, agricultural villages and farmsteads have not received as much attention. The advent of survey archaeology, which systematically records sites and artifacts across the landscape, allows estimation of settlement patterns and population trends during different sequential periods of occupation. Guidoboni et al. (2000) analyzed the archaeological data around the area of southern Italy and Sicily that was affected by the 1908 M7 earthquake in the Strait of Messina; they concluded that evidence of earthquakes can be identified based on changes in habitation patterns. From the archaeological survey data, in conjunction with epigraphic, archaeological collapse horizons, reuse of inscribed blocks, and potential tsunami deposits, they suggest that contraction of settlements was a response to a large damaging earthquake circa 350–363 CE. Guidoboni et al. (2000, 45) call this method "territorial archaeoseismology."

Several papers have highlighted how earthquakes at archaeological sites, if not independently dated through artifactual or numismatic means, can lead to circular reasoning (e.g., Ambraseys, 2005, 2006; Rucker and Niemi, 2010). In such cases, historical earthquake catalogs are used to assign dates to archaeological collapse horizons, and then the evidence of collapse from the archaeological site is entered into the earthquake catalog as evidence for a particular seismic event. Because earthquake catalogs are inherently incomplete, this practice can lead to amalgamation and distortion of seismic event dates and locations. As is clear across all subdisciplines of geoarchaeology, interpretive problems can be avoided largely through direct field collaboration between archaeologists and earth scientists within an interdisciplinary or multidisciplinary approach to research (e.g., Guidoboni, 1996; Ambraseys, 2006).

Understanding the tectonic, geologic, and geomorphic setting of an archaeological site has long been recognized as fundamental to understanding archaeoseismic evidence (e.g., Karcz and Kafri, 1978; Rapp, 1986). Sintubin and Stewart (2008) proposed a two-branch logic tree that can

**Archaeoseismology, Figure 3** (Continued) be utilized to evaluate whether an archaeological site is favorably located to record earthquake damage (site potential factor) and the extent to which features can be used as evidence for an earthquake based on the type of damage, its dating, and regional distribution (Figure 2). These authors introduce an archaeoseismic quality factor (AQF) as a numerical means to evaluate confidence levels for the archaeoseismic data. The AQF has been applied to a couple of sites, including Sagalassos in southwestern Turkey (Sintubin and Stewart, 2008) and Baelo Claudia in southern Spain (Grützner et al., 2010).

## Archaeological evidence of past earthquakes

### Earthquake damage to structures

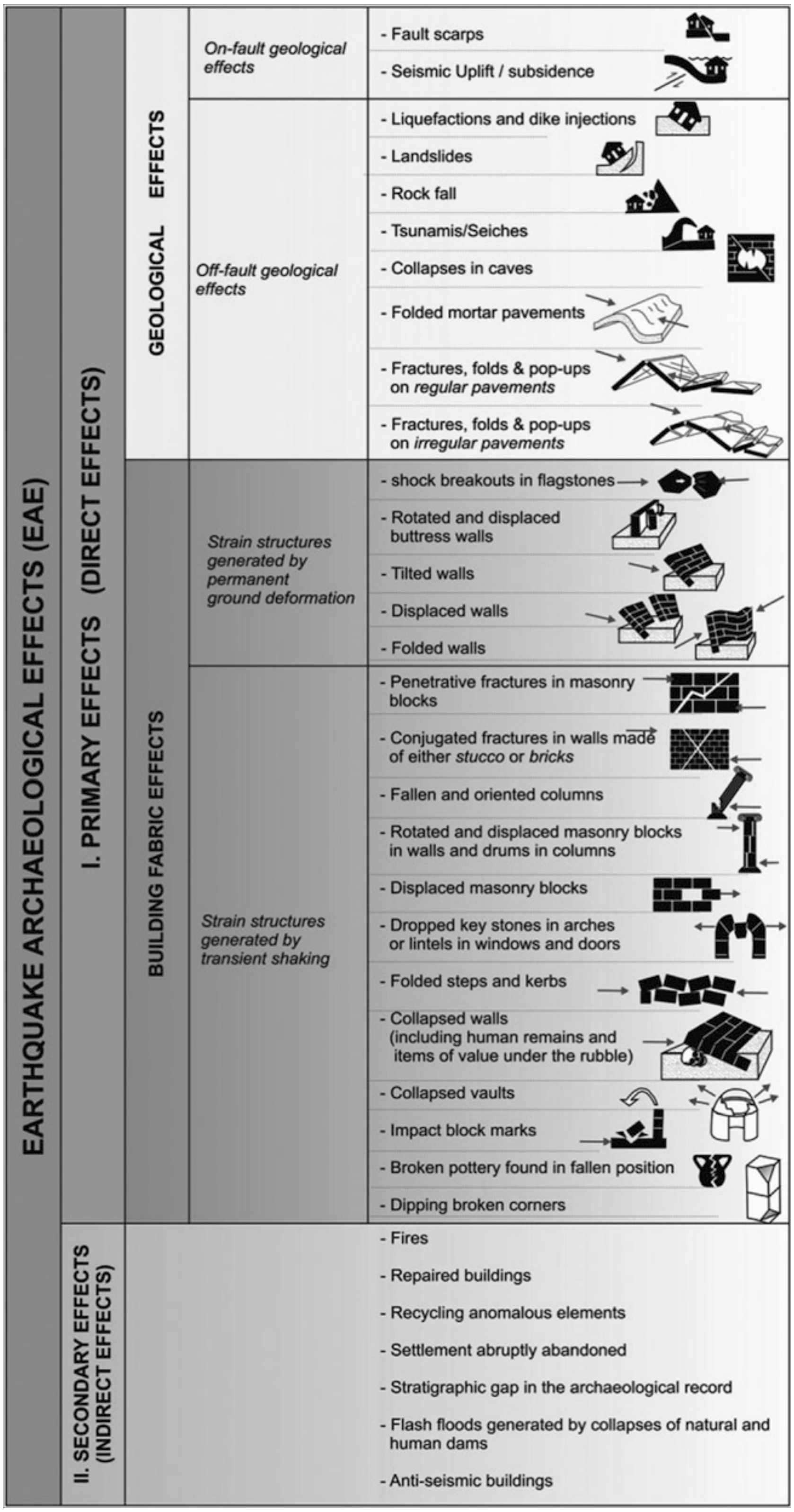
Stiros (1996) provided one of the first published lists of criteria to identify earthquake damage at an archaeological site. Buildings of blocks (brick or stone) and mortar behave differently from a building of large dimensional stones set on top of each other (dry masonry). Buildings of mudbrick or wood framing also have a specific response to seismic shaking. Much of what has been developed in archaeoseismology has focused on the Mediterranean region. Characteristic seismic damages to structures, here summarized from Stiros (1996), Galadini et al. (2006), and Hinzen (2009), include: (1) cross fissures in the vertical plane due to shear forces and diagonal cracks in rigid walls; (2) triangular corner expulsion due to orthogonal motion of walls; (3) lateral and rotational horizontal and independent motion of blocks within a wall, seen as open vertical fractures; (4) height reduction due to vertical crashing; (5) deformation of arch piers including collapse of keystones; (6) wall tilting and distortion; (7) rotation or toppling of pillars and column drums often aligned in a row or laid out “domino style”; and (8) impact of architectural elements on pavement. Photographic examples of these features are shown in Figure 3.

Scientific inquiry into the fall direction of monuments, statues, and structures largely began with Robert Mallet’s (1862) investigation of the 1857 Naples earthquake in Italy. Numerous investigators have postulated that the fall direction of building columns or column drums and other architectural elements of a building has azimuthal relevance with respect to the causal earthquake. It should be evident, though not always acknowledged, that freestanding columns or monuments, such as an obelisk, will respond differently from a line of columns supporting a structure, such as a temple or church. A column that is carrying a load, like the superstructure of a building, is not free to fall in any direction. Numerical modeling of a single standing column using “input motion from 29 - strong-motion records indicates little correlation between downfall directions and back azimuth” (Hinzen, 2009, 2855). This study showed that, although columns often fall in a parallel alignment, the data cannot be used to determine the direction to the earthquake epicenter.

A variety of scales have been developed to quantify the intensity of ground shaking and the effects of an earthquake on people and animals, as well as damage to the built environment (e.g., the modified Mercalli scale). To measure earthquake intensity from seismically induced ground features recorded in the natural environment, the International Union for Quaternary Research (INQUA) developed the environmental seismic intensity (ESI) scale (Michetti et al., 2007). More recently, Rodríguez-Pascua et al. (2011) proposed an earthquake intensity scale for seismic damage at archaeological sites called the Earthquake Archaeological Effects (EAE), which is modeled after the ESI scale (Figure 4). The EAE scale divides earthquake damage into two categories: (1) those events affecting building fabric, either from seismic shaking of the superstructure or strain on the foundation, and (2) geologic effects on ancient buildings caused by faulting or other seismically induced ground failures. It is clear, however, that many of the features in the EAE scale (e.g., tilted or displaced walls, deformed or fractured pavement, cave or other structural collapses, among others) can occur under natural soil movement and gravitational conditions without invoking seismic excitation. Therefore, identification of one or two features in the EAE scale should not be interpreted as evidence for an earthquake without assessing the geological conditions of the site or performing something equivalent to the AQF test.

Quantification of earthquake damage at archaeological sites is complicated, as the conditions of the building before and after the earthquake in antiquity are not known. Extant buildings may have also experienced ground motion from multiple earthquakes originating from different source areas. Stiros (1996) cautions that recognition of earthquake damage can be assured only if other mechanisms of deformation such as differential ground subsidence, gravitational ground failures (i.e., slumps, landslides, rockfalls, etc.), shrinking and swelling soils, or poor construction, among other natural and structural engineering issues related to building collapse and failure, can be eliminated. Many fractures, warps, and collapses cannot unequivocally be designated as damage from an earthquake.

**Archaeoseismology, Figure 3** Evidence of earthquakes at various archaeological sites: (**a**) destruction horizon at the Chalcolithic site of Hujereit al Ghuzlan in Aqaba, Jordan; (**b**) fallen columns at Petra, Jordan; (**c**) shifted keystone at the Crac des Chevaliers Crusader castle in Syria; (**d**) rotated, horizontally shifted blocks of gypsum at the Roman fortified city of Dura-Europos in Syria – in this case, the deformation is caused by military undermining of the wall during the siege of the city; (**e**) the collapsed wall of the city gate at Hierapolis, Turkey; (**f**) fracture crossing a stepped cistern at the Qumran site in Israel – the fracture is likely due to unstable lake marls beneath the reservoir rather than a through-going fault; and (**g**) impacted pavement at the Magnesia site, Turkey.




**Archaeoseismology, Figure 4** The Earthquake Archaeology Effects seismic intensity scale divides earthquake damage into events affecting the building fabric, either from seismic shaking of the superstructure or strain on the foundation, or those geologic effects on ancient buildings caused by faulting or other seismically induced ground failures (After Rodríguez-Pascua et al., 2011).

Several studies have used detailed mapping of damage to extant archaeological structures to calculate ground motion that created the structural failures. Hinzen (2005) modeled the natural reactions of the soil under conditions of a local source earthquake and the resultant displacement to an ancient construction. He concluded that an earthquake caused the wall cracks, displacements, and rotations in the Roman fortifications at the Tolbiacum site in Germany. Kamai and Hatzor (2008) used the discontinuous deformation analysis method to calculate the peak ground acceleration that produced slipped keystones of arches at the Mamshit and Nimrod Fortress archaeological sites in Israel. These methods hold promise for quantifying earthquake parameters from archaeological data.

## Coseismic offset at archaeological sites

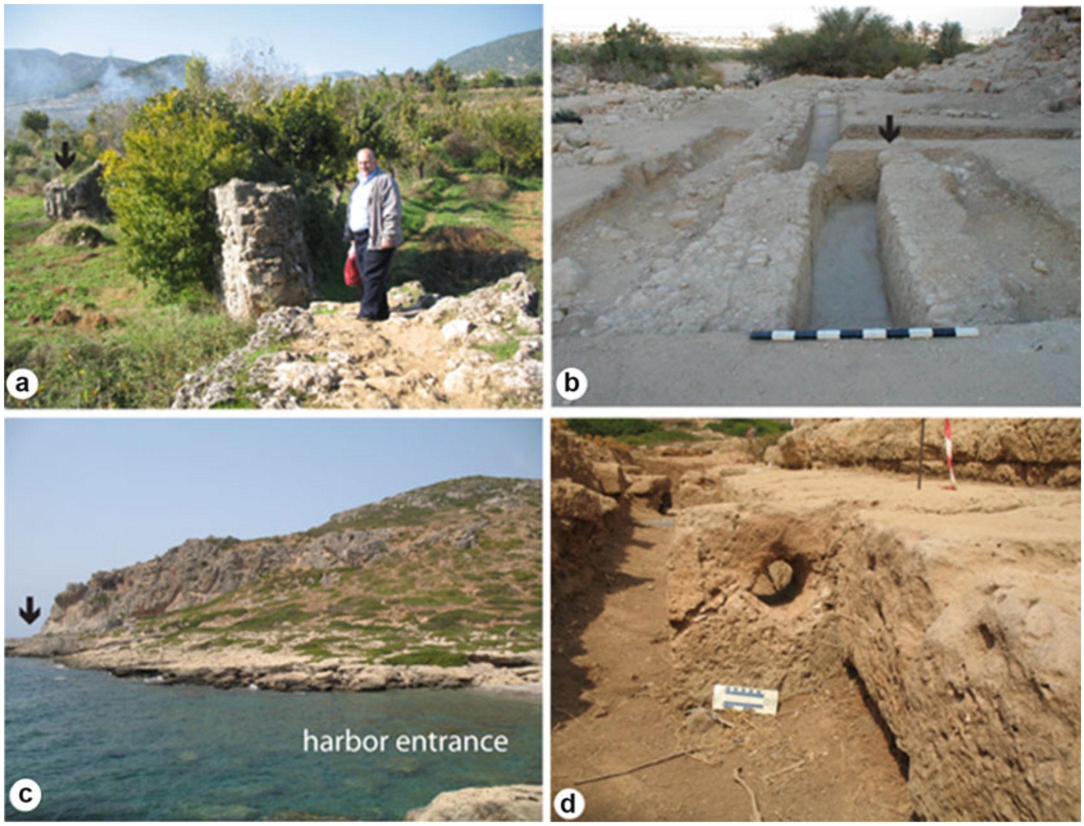
One of the ways archaeological data can be used to quantify a seismic source is to define the amount of fault slip from a past earthquake (i.e., coseismic slip). Based on modern empirical relationships between earthquake magnitude and fault slip (e.g., Wells and Coppersmith, 1994), matching features that were offset across a fault, whether they are natural geologic (such as a riverbed) or cultural (such as a wall), can lead to estimation of the magnitude of an ancient earthquake. The advantage of utilizing archaeological piercing points (points that can be matched across a fault that have been displaced by an earthquake) is that they can often be more precisely dated than geologic deposits. The type of fault offset expected at an archaeological site depends on its tectonic setting. Thus, any number of deformations can be expected including strike slip (horizontal displacement), dip slip (vertical displacement), or oblique slip (both horizontal and vertical displacement), and land level changes due to tectonic uplift, subsidence, or folding. Offset archaeological data were summarized in Noller (2001), although additional work has clearly been conducted since his compilation.

The isolated observation of a single offset architectural feature from an archaeological site is not sufficient to differentiate between coseismic faulting and other shear plane failures, such as landslides. Landslide scarps, tensional fractures, and other features due to gravitational sliding can also produce offsets at an archaeological site. It is necessary to map the areal extent of fractures or offsets in order to interpret whether they represent an arcuate landslide scarp or a through-going fault rupture. Aseismic differential settling of a structure can also produce features that appear like fault offsets (e.g., Karcz and Kafri, 1978). Therefore, the interpretation of offset strata or structures at an archaeological site needs to be evaluated within the context of geologic and geomorphic site characterization.

Strike-slip faults laterally offset features either in a right- or left-shear sense across the fault or in a combined oblique slip. Perhaps one of the earliest and most spectacular documentations of offset is the three-meter right-lateral and two-meter horizontal displacement of the Great Wall of China in the 1739 earthquake (Zhang et al., 1986). A number of studies have documented strike-slip offset of ancient architectural features across the Dead Sea Transform (Figure 5). These include the fortification wall of the Crusader castle of Vadum Jacob (Ateret fortress) in northern Israel (Marco et al., 1997), the aqueduct and reservoir at Byzantine Qasr Tilah in Jordan in Figure 5a (Haynes et al., 2006), Neolithic tell and Roman road near Antakya, Turkey (Altunel et al., 2009), and the Al Harif Roman aqueduct in Syria (Meghraoui et al., 2003; Sbeinati et al., 2010). The last study clearly shows that after the first two fault ruptures, the aqueduct was repaired preserving a left-lateral bend. Archaeological sites that lack architecture can also be used to measure coseismic slip as is exemplified in the displacement of Native American middens along the San Andreas fault system in California (Noller and Lightfoot, 1997; Noller, 2001).

Extensional tectonic areas (regions where the continent is being stretched) are characterized by normal faults with steep triangular-faceted mountain fronts adjacent to linear valleys. Because of the abundance of normal faulting in Greece, western Turkey, and Italy and the extensive Bronze Age through Classical period archaeological excavations, many archaeoseismologic studies describing earthquake damage have been published from this region. However, few studies document direct normal-fault slip of archaeological remains, but rather show activity of normal faults adjacent to a site, as in the study of the Helike fault in Greece (Koukouvelas et al., 2001). The Helike fault study also suggested regional Gulf of Corinth tectonic subsidence to partially explain the burial of the Helike archaeological site. Hancock and Altunel (1997) report offset walls and water channels from the Roman to late Byzantine period at the site of Hierapolis in Turkey. Other examples of normal fault offset include a 4-m offset of a Roman aqueduct in southern Italy (Galli et al., 2010) and small offsets in Sicily (Barreca et al., 2010).

Tectonic geomorphological studies in convergent tectonic regions show that surface deformation in a compressive earthquake is complex. Depending on the specifics of the tectonic setting and the location of the archaeological site, an earthquake can produce fault rupture, or surface subsidence or uplift. Harbor sites are particularly good in recording deformation because sea level provides a datum for land level changes. The site of Phalasarna in western Crete was identified as early as the 1850s as an uplifted ancient harbor (Figure 5). Stefanakis (2010) summarizes the extensive research conducted into the great subduction zone earthquake of 365 CE that produced about eight to nine meters of coseismic uplift, leaving the ports of Phalasarna and Kissamos isolated. This earthquake also caused a devastating tsunami that crossed the eastern Mediterranean. Identification of tsunamis in archaeological context is discussed elsewhere in this book.




**Archaeoseismology, Figure 5** An archaeological site that is located directly over an active fault may record offset of an architectural feature or other anthropogenic layer in an earthquake, including: (**a**) offset of the Al Harif Roman aqueduct in Syria, (**b**) offset of the aqueduct by about 2 m at the Qasr Tilah site in Jordan (Haynes et al., 2006), (**c**) the ancient harbor of Phalasarna in Western Crete was uplifted more than 8 m in the earthquake of 365 CE (e.g., Stefanakis, 2010), and (**d**) detail of the port boat ties.

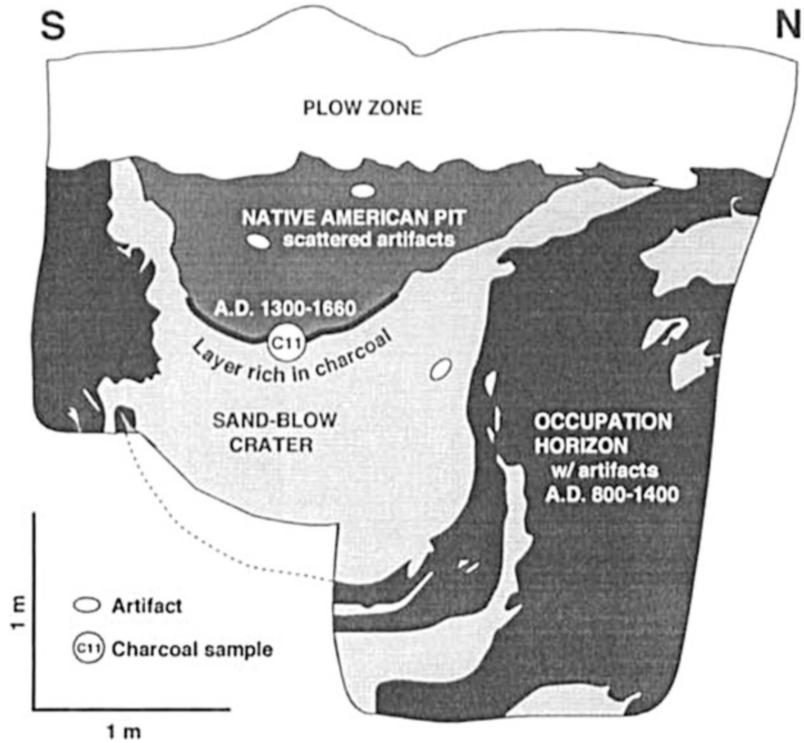
## Liquefaction

In many areas of the world, the archaeological record does not include an abundance of monumental stone buildings. Consequently, methods to decipher earthquakes in the Mediterranean do not necessarily transfer readily to other regions of the world. In areas where the predominant building style is post and wall construction with organic materials, as is typical in many seminomadic cultures, or where building traditions preclude heavy masonry because of building tradition or lack of suitable resources, other methods of describing earthquake damage need to be devised. One successful method to document earthquakes in these regions is mapping and dating liquefaction features within archaeological sites.

Liquefaction occurs when shallow, saturated, loose sand loses strength and flows due to cyclical loading of seismic waves. Several features are diagnostic of liquefaction, including fluidized sedimentary structures, sand dikes, sand sills, sand blows and craters, land subsidence, and lateral movement (spread) of surface sediment toward topographically low areas. Native American occupation sites and artifacts buried or deformed by liquefaction (Figure 6) have been extensively used to date paleoearthquakes in the New Madrid seismic zone in the stable craton (interior) of North America (e.g., Tuttle et al., 1996, 2011). Other pioneering work utilizing liquefaction features to date earthquakes at archaeological sites has been conducted in Japan. Barnes (2010) provides a comprehensive summary of the Japanese archaeoseismologic studies.

## Summary

The field of archaeoseismology developed out of dual needs: (1) to verify the historical record of earthquakes at sites and (2) to document earthquakes that are silent in the historical accounts but may have played a pivotal role in local and regional cultural history. Damage from earthquakes at archaeological sites has been widely observed in stratigraphic destruction horizons and in damaged architectural features and buildings. Cracks, fissures, tilted, distorted, and displaced walls, columns, floors, and pavements, slipped keystones, collapsed but aligned columns and walls, subsidence, slides, warping, and other deformations of the architectural elements of buildings and other




**Archaeoseismology, Figure 6** Liquefaction features from the New Madrid seismic zone of the Central United States showing a sandblow crater formed in an earthquake that buries and deforms the lower occupation layer. Younger Native American deposits are found on top of the sandblow feature (After Tuttle et al., 1996).

structures have been cited as evidence of earthquake damage. This type of data cannot be interpreted as seismically induced until other causes have been eliminated.

In addition to dates of past earthquakes, archaeoseismic methods can provide either a measure of the amount of coseismic slip or the intensity of ground motion, both of which can be used to estimate the magnitude and epicenter of a paleoearthquake. In areas with a tradition of predominantly timber construction, the typical physical evidence of earthquake damage may be liquefaction. Working directly with the archaeologist in the field through an interdisciplinary approach or using unpublished original plans, maps, section drawings, and field notes is preferable to relying on published archaeological summaries. Archaeoseismology is a new and developing field that is evolving from its early focus on qualitative observations to more recent measurement of quantitative data to learn about past earthquakes.

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## ARCTIC GEOARCHAEOLOGY: SITE FORMATION PROCESSES

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### Definition

Arctic geoarchaeology is concerned with how natural processes affect archaeological site formation in high-latitude northern environments. Perhaps the most significant site formation issue that produces the most serious problems in Arctic geoarchaeology is cryoturbation, which is the effect of repetitive freezing and thawing on sediment and soil. Frost heaving, gelifluction, and ice wedging are the most common cryoturbation processes that can significantly alter archaeological site matrices, disturbing stratigraphic order and displacing artifacts vertically and horizontally.

### Frost heaving

Frost heaving results from upward movement of ground materials during freeze-thaw events (Taber, 1929). At archaeological sites, this process can reorient artifacts and ecofacts (Johnson and Hansen, 1974; Johnson et al., 1977). Much of the Arctic is underlain by permafrost, which is soil or other substrate that is permanently frozen, often to great depths. In the warm months, the upper, active layer of the ground thaws, but the still frozen base prevents drainage, leaving the surface generally covered by wet, hydromorphic soils. Winter brings freezing conditions and ice forms within the saturated, frost-susceptible sediment. As it does, it expands upward in the direction of heat loss (Konrad, 1999), which is the only direction in which it can expand as it is blocked by permafrost below. This upward movement squeezes large objects such as rocks and artifacts as freezing water expands in volume with great force, thrusting them upward as well (Bowers et al., 1983). Under certain conditions, frost heaving eventually produces patterned ground, where the repeated freeze-thaw cycles sort large stones and finer sediments into polygonal or linear geometrical shapes (Kessler and Werner, 2003). The longer an artifact is in the ground, the more it can be displaced (Johnson et al., 1977).

Telltale signs at sites affected by frost heaving include (1) large-sized artifacts found in on-surface or near-surface positions and (2) vertical orientation of buried, displaced artifacts (Schweger, 1985). Archaeological sites in areas of tundra, especially sites of greater age, can be completely unstratified through the effects of frost heaving acting over many centuries to move artifacts from initially layered deposits below ground to mostly near-surface positions (Thorson, 1990; Holliday, 2004, 279).

### Gelifluction

The process of gelifluction occurs where snowfall accumulation is great, sediment overlying permafrost annually thaws and refreezes, and the ground surface is sloped. Rapid melting of snowfall in spring saturates the upper sediment zone. On a slope, saturated sediment succumbs to gravity, flowing or creeping downslope over the underlying impermeable permafrost zone. Displaced materials then refreeze in their new locations during autumn, creating ribbon-like involutions or folds of the upper sediment zone and displacing associated archaeological materials both vertically and laterally. As the lobes of gelifluction sediment bulge downhill, they can attenuate upslope cultural deposits, thinning them sometimes to the point of leaving gaps as the mobile material bunches and folds over itself downslope (Hopkins and Giddings, 1953; Thorson and Hamilton, 1977; Holliday, 2004, 279–281).

### Ice wedging

Ice wedges form when sediment overlying permafrost becomes freeze-dried, contracts, and cracks under the cold, winter conditions. Due to tensional forces acting on the sediment, these cracks form in a polygonal pattern on the ground surface (patterned ground), but below the surface, the cracks can penetrate to permafrost depth. During the summer months, snowmelt seeps into and fills the cracks and then refreezes during the subsequent winter months. As this water freezes, it expands to form an ice wedge. The following year, the cycle repeats as the ice wedge cracks and seepage fills it again. The process continues so that year after year this cycle of crack, thaw, and freeze widens and deepens the ice wedge. The implications for geoarchaeology are that surface sediment and artifacts can slip down into the cracks, entrained by meltwater seepage, as additional materials filling the ice wedges as they grow. As ice thaws, deformed fill features or ice-wedge pseudomorphs are left behind (Lachenbruch, 1962).

### Pseudo-paleosols

A further behavior of soils in Arctic environments involves the concentration of fine particulate matter to form dark layers resembling buried paleosols. Under moist but not saturated soil conditions, thin layers of organic material, clays, and silts can be sorted by the freezing process seasonally, creating a layer that, in warmer months, traps downward moving illuvium, thereby producing color banding that appears to be a buried ancient soil (Thorson, 1990, 406; Holliday, 2004, 281).

### Cryoturbation in pleistocene age sites

During the glacial advances of the Pleistocene epoch, Arctic-like conditions moved southward in step with the expanding ice sheets and down the slopes of high mountains carried by the ice flows emanating from upper elevations. Ancient sites dating to the last ice age can also display signs of cryoturbation given the extreme cold of the time. Lower and Middle Paleolithic remains in Britain are often found in alluvial terrace fill, which preserves the best record of such periods (Basell et al., 2011). Cryoturbation features illustrating the effects of frost heaving, gelifluction, and ice wedges have been found in such sites indicating periglacial or frost conditions (Basell et al., 2011, 29). Similarly, the effects of cold conditions due to the Last Glacial Maximum can be seen in the sediments and soils of Upper Paleolithic sites buried in alluvium in the Kostenki area along the Don River in southwest Russia (Holliday et al., 2007). On the Seward Peninsula of western Alaska, a fluted-point site dating to 12,400 calendar years ago shows evidence of cryoturbation in the form of frost-shattered grains and lenticular pores, suggesting the presence of ice in the soil (Goebel et al., 2013).

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### Cross-references

Beringia, Geoarchaeology
Glacial Settings
Kostenki, Russia

## ARTIFACT CONSERVATION


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### Definition

Conservation of archaeological finds is a critical part of excavation and curation. It is the activity that assures the permanence of the physical artifacts and preservation of the information they contain, and it includes specific methods and standards for examination, documentation, treatment, and preventive care of archaeological materials. These activities are performed by specialists who belong to professional societies that promote education, research, and adherence among its practitioners to a code of ethics and standards of practice.

### History

When an early human repaired or rejuvenated a stone tool to extend its working life, he was not engaged in conservation as we now understand the term since the preserving activity did not result from an academic tradition of research and education to explore and improve upon the suitability and compatibility of methods and materials. In Europe, it was not until the Renaissance when such an approach was applied to antiquities; sixteenth-century restoration practices were recorded by Benvenuto Cellini in his memoirs (Cellini, 1823). Subsequent discoveries of fragile finds at archaeological sites in Egypt, Italy, the Near East, and elsewhere showed the need for a disciplined approach to the development of preservation practices based on testable methods. In the eighteenth and nineteenth centuries, that need was met by the application of the scientific method in what would eventually become the field of materials science. Investigations of specific ancient materials began the process of consolidating the research and recommended methods of the previous century; these appeared in texts such as *The Preservation of Antiquities* by Friedrich Rathgen (1905) and a book of the same title by Harold Plenderleith (1934) which was subsequently expanded and updated as *The Conservation of Antiquities and Works of Art: Treatment, Repair and Restoration* until its final printing (1974). The discovery of Tutankhamen's tomb with its wealth and diversity of antiquities spurred research in archaeological materials science at the British Museum under Arthur Lucas (1926). These efforts together with those of other research centers formed the foundations of what would become academic postgraduate or certificate programs of study starting in the 1930s at Harvard's Fogg Art Museum and University College London's Institute for Archaeology. Today, universities and other cultural organizations throughout the world train conservators in graduate schools and certificate programs. Worldwide professional societies, such as the International Institute for Conservation (IIC) and the American Institute for Conservation of Historic and Artistic Works (AIC), support conservators by sponsoring journals and congress proceedings for the publication of juried research. UNESCO's International Council of Museums supports the Council for Conservation (ICOM-CC), which hosts a worldwide triennial congress of conservation.

## Professional activities

This entry will introduce the professional activities of the conservator. Recent comprehensive studies can be found in *Conservation Treatment Methodology* (Appelbaum, 2007); *Conservation Skills: Judgement, Method, and Decision Making* (Caple, 2000); *Contemporary Theory of Conservation* (Muñoz Viñas, 2005); and *Conservation: Principles, Dilemmas and Uncomfortable Truths* (Richmond and Bracker, 2009).

### Examination

Conservators examine artifacts to determine composition and condition prior to considering whether a treatment is needed. They approach every artifact individually and spend a considerable amount of time in this initial phase. Typical protocols for examination start with naked eye inspection under standard and raking visible light as well as ultraviolet light to detect common autofluorescent materials. Microscopic analysis often follows using a - low-power reflected light inspection microscope to begin characterizing minor components. Micro-sampling of these components may be done at this point and the samples mounted for polarizing transmitted light microscopy to further identify and describe the actual physical condition of the artifact. More technical examinations include x-ray fluorescence spectroscopy and x-ray diffraction to identify elemental and mineral components, respectively. Many other analytical methods are used as needed.

Though examinations are done in preparation for treatment, thorough explorations of artifacts whose construction is unfamiliar to specialists in the field can become ends in themselves, and they may be published without reference to any treatment phase under the rubric of technical studies. For example, in their paper "An Egyptian cartonnage of the Graeco-Roman period: Examination and discoveries," Scott et al. (2003) relate their discovery of unexpected pigments and construction techniques in a 350 BC coffin liner from ancient Egypt. Here, the conservators and conservation scientists brought together diverse technologies such as radiocarbon dating, x-ray diffraction analysis, energy-dispersive x-ray fluorescence, Fourier transform infrared spectroscopy (FTIR), thin-layer chromatography, and gas chromatography with mass spectrometry (GC-MS) to show the influence of contact with Roman culture on traditional Egyptian practices.

### Documentation

The results of each artifact examination are recorded in a standardized treatment database along with other essential information, such as dimensions, detailed condition descriptions, and photo-documentation. The practice of photographing artifacts before and after treatment is a hallmark of conservation, as the appearance of artifacts can change due to the treatment. Care is taken to record accurately those characteristics of identification and condition such as color, surface condition, completeness, and size. Catalog numbers are always included in the frame of the photograph along with a color balance card and metric measurement scale. Typically, at least six overviews are taken of three-dimensional objects, four side views, a top view, and a bottom view. Additional close-ups or detail views are added as needed to document the pretreatment state. The importance of documentation and especially photo-documentation has caused these practices to be periodically codified through publication. See, for example, *The AIC Guide to Digital Photography and Conservation Documentation* (Warda, 2011).

### Treatment

Proposed treatments are determined by the preceding examination. Because the artifacts are considered to contain archaeological data, the conservator generally limits treatment as much as possible to stabilization, and materials applied in this process should be removable, i.e., procedures should be reversible in the ideal. Waterlogged wood objects will crack when dried in air, so they receive treatments with intracellular bulking agents, such as polyethylene glycol, to maintain their dimensions after drying. Without such treatment, the wood might deform into a shape having no resemblance to either its original form or that which it had when recovered in the field. After recovery, some metal artifacts can begin to corrode rapidly in air; these will require treatments to remove the soluble salts that catalyze such corrosion. Textiles and other fibrous artifact fragments are among the most challenging to conserve. They can disintegrate during initial field inspection and, as a result, often require a method called blocklifting, wherein the artifact is kept encased in its surrounding soil or sediment and the entire sediment block is removed to a conservation laboratory where it can be micro-excavated under controlled conditions. Heavily corroded artifacts and complex composite artifacts can also require block retrieval. The care and ingenuity that such lifting techniques require in the field are described in Robert Payton's edited volume, *Retrieval of Objects from Archaeological Sites* (1992), including the recovery of 30 ton sculptures from Argo Island on the Nile and the extremely fragile human remains at Herculaneum.

Often excavations can be collaborative with the archaeologist and conservator listening closely to the wishes of the local community, including heritage groups and descendant groups. *Collaborating at the Trowel's Edge*, an edited volume by Steven Silliman (2008), and *Preserving What Is Valued*, by Miriam Clavir (2002), describe the breadth and complexity of the working relationships that result from community-based research. Such relationships can change the routine academic priorities of conservation performed simply as data preservation. Indigenous peoples are often collaborators with a strong concern for how the earth and its recovered artifacts are handled during and after an excavation. Sacred artifacts will usually receive no conservation treatment in order to preserve their unique unaltered state and avoid leaving preservative agents within the artifact that may be viewed as contaminants. Nonsacred artifacts having special significance to the local community will often receive extra conservation care as these objects often become symbols of local heritage.

## Preventive care

Conservators limit the preservative chemicals they apply to all cultural objects. Archaeological collections that are curated primarily for their data require even greater attention because any resinous coating, consolidant, or other chemical can interfere with future chemical analyses. The archaeological conservator then attempts to provide preservation to control physical and environmental deterioration. These can include custom cushioned storage mounts that support weak areas and allow casual inspections without direct handling of the artifact. Termed housing or rehousing techniques, these supports can be enclosed to make passive microenvironmental control possible. Buffered or desiccating silica gel may be added to enclosed storage units or even to individual object housings to limit the range and rate of fluctuation in relative humidity. Instructions for preventive care are often included as part of the treatment database. See Carolyn Rose and Amparo Torres, *Storage of Natural History Collections*, for this aspect of preservation through environmental modification in the museum setting (Rose and de Torres, 1992). In the fieldwork setting, a recent offshoot of this focus on the modification of the environment is the movement toward *P*reservation of *A*rchaeological *R*emains In Situ (PARIS). In this application of preventive care, sites that cannot be excavated for some reason are remotely monitored to prevent damage from, for example, soil water table fluctuations, which could decrease the preservation of organics and metals in burials (Kars and van Heeringen, 2008).

## Research

Besides their close work with archaeologists and curators, archaeological conservators also maintain a tradition of research and publication that is independent of the scholarship devoted to the interpretation of artifacts. It is in large measure practical research meant to develop new or improved methods for the examination, analysis, treatment, and care of artifacts. Most investigations of this kind focus on how to characterize the materials of which artifacts are made, how those materials degrade, and how to apply new materials and technologies to their preservation. The research is published mainly in journals of the conservation community's professional societies and institutions, including *Studies in Conservation* (the journal of the International Institute for Conservation), the *Journal of the American Institute for Conservation*, *The Conservator*, the *Journal of the Institute of Conservation* (London), and the Research and Conservation series of the Getty Conservation Institute.

Because conservation is highly interdisciplinary, it also gathers information from wide-ranging areas of research, including anything from the latest filling materials used in modern dentistry to the lives of subterranean termites and the damage they do to wood. Such data are best accessed through two custom online, searchable databases: the Conservation Information Network and Art and the Archaeology Technical Abstracts Online.

Other databases include those that evaluate the common properties of the chemicals and commercial materials used in the treatment of artifacts. They represent an essential resource to conservators because the formulas for commercial materials are changed by their manufacturers over time. Two of these databases are the Conservation and Art Materials Encyclopedia Online (CAMEO) and the Art Materials Information and Education Network (AMIEN). They are always consulted since every treatment requires its own research.

## Education

Until the mid-twentieth century, conservation training took the form of apprenticeships under recognized conservators. Archaeological object conservation was a subdivision of museum objects conservation, which tended to concentrate on the aesthetic aspects of artifacts rather than on details such as use-related wear and accretions due to long intervals of surficial deposition or chemical alteration. As archaeological conservation developed, such details became a focus for study and preservation, as they contain information about the unique histories of individual artifacts. This approach is now central to the conservation of artifacts as archaeological data. For example, surface stains that would previously have been removed as disfigurements are now preserved for interpretation by the archaeologist. Ultimately, this trend toward viewing all aspects of an artifact as potential data has led to the current goal of preserving archaeological artifacts in ways that will make the least alteration and leave the fewest residues.

Since the mid-twentieth century, university-based graduate programs in art and historical artifact conservation have emerged around the world, and this is now the dominant way that new practitioners enter the field (though some internship programs continue to offer certificates in select specialties). Since the 1970s, graduate programs have recognized the trend toward specialization and started incorporating museum and field archaeological materials as areas of instruction and study; such programs exist at the University of California at Los Angeles, University College London, and the University of Applied Science in Berlin.

## Ethics

Archaeological conservators are charged with recognizing, preserving, and enhancing the information potential of an artifact in ways that do not compromise future study, and they accomplish this without interpreting its meaning, characterizing its place of provenance, function, authorship, or date. This is analogous to preserving a book without commenting on its text. In this role, conservators approach their work very conservatively with respect to actions that change the artifact, even in small ways. For instance, routine artifact cleaning methods must be considered carefully since the wrong application could unintentionally strip off use-related substances or leave behind detergent residues that could confound future organic microanalyses. This position of advocacy for the uninterpreted artifact distinguishes the archaeological conservator from those disciplines that use the collections to reconstruct human behavior. Conservators can sometimes be so protective of cultural property that they seem to discourage any use of it for data acquisition, but, in fact, compromises are always reached that promote stable collections management while facilitating academic study and exhibition. Noninvasive analytical methods are usually promoted over those that require sampling of the artifact. Appropriate handling methods are routinely followed to lessen the wear and tear on artifacts during study. Recently, the issue of preservation sustainability has received increased attention as part of the mix of compromises that the ethical conservator must consider.

## Geoarchaeological conservation

The act of unearthing an artifact can create physical and chemical instabilities that often lead to the artifact's deterioration with consequent loss of data. Prior to its excavation, the artifact lies in soil or other sediment, its weight supported by the matrix, and often at chemical and biological equilibrium with its surroundings. When it is first buried, the artifact becomes part of an evolving microenvironment that is related, but not identical, to the general sediment environments of the site. In practical terms, the artifact will either (1) decay, disintegrate, and disappear as an intact object within the site soil, or (2) it will develop a boundary layer at its surface brought about by local geochemical and biological conditions. Examples of these alteration boundaries include simple discolorations, corrosion layers on metal objects, or insoluble salt accretions on wood, ceramics, and other materials. The initial boundary, which can appear as a crust, a softened layer, or a discoloration, can be unstable and invasive, eventually destroying the artifact, or it can be stable and insulating, protecting the artifact from the surrounding sediment. Many materials form such boundary layers. Wooden artifacts, when degrading within wet sediments, will experience a buildup of toxic byproducts at their surfaces that gradually slow the rate of biodeterioration as the artifact – i.e., the food source – becomes less attractive to destructive bacteria and other organisms. Some metal artifacts form thin corrosion layers that transform the object's surface and prevent the underlying metal from further loss. Once formed, such layers must often be preserved along with the rest of the artifact because they may retain the original surface patterning; removing them in order to return the artifact to an unaltered appearance can actually strip away important surface detail. These boundary/alteration layers also yield clues to the geochemistry of the site soil or sediment, providing information that can be used to understand site formation processes. By focusing on preserving the artifact's surficial boundary layer, geoarchaeological evidence relevant to soil conditions, alteration, diagenesis, and other aspects of the burial environment may be conserved.

## Summary

Artifact conservation is a young and rapidly developing field. Conservators continue the traditional activity of creating new and better methods of artifact treatment in order to safeguard the collections that form the basis of archaeological inference. At the same time, the conservation profession is evolving and expanding as an academic discipline, offering its own insights into artifact microanalysis and site development processes.

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## Cross-references

Ceramics
Chemical Alteration
Electron Probe Microanalyzer
Fourier Transform Infrared Spectroscopy (FTIR)
Gas Chromatography
Glass
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Lithics
Metals
Organic Residues
Radiocarbon Dating
Site Preservation
X-ray Diffraction (XRD)
X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology

## ATAPUERCA

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### Definition

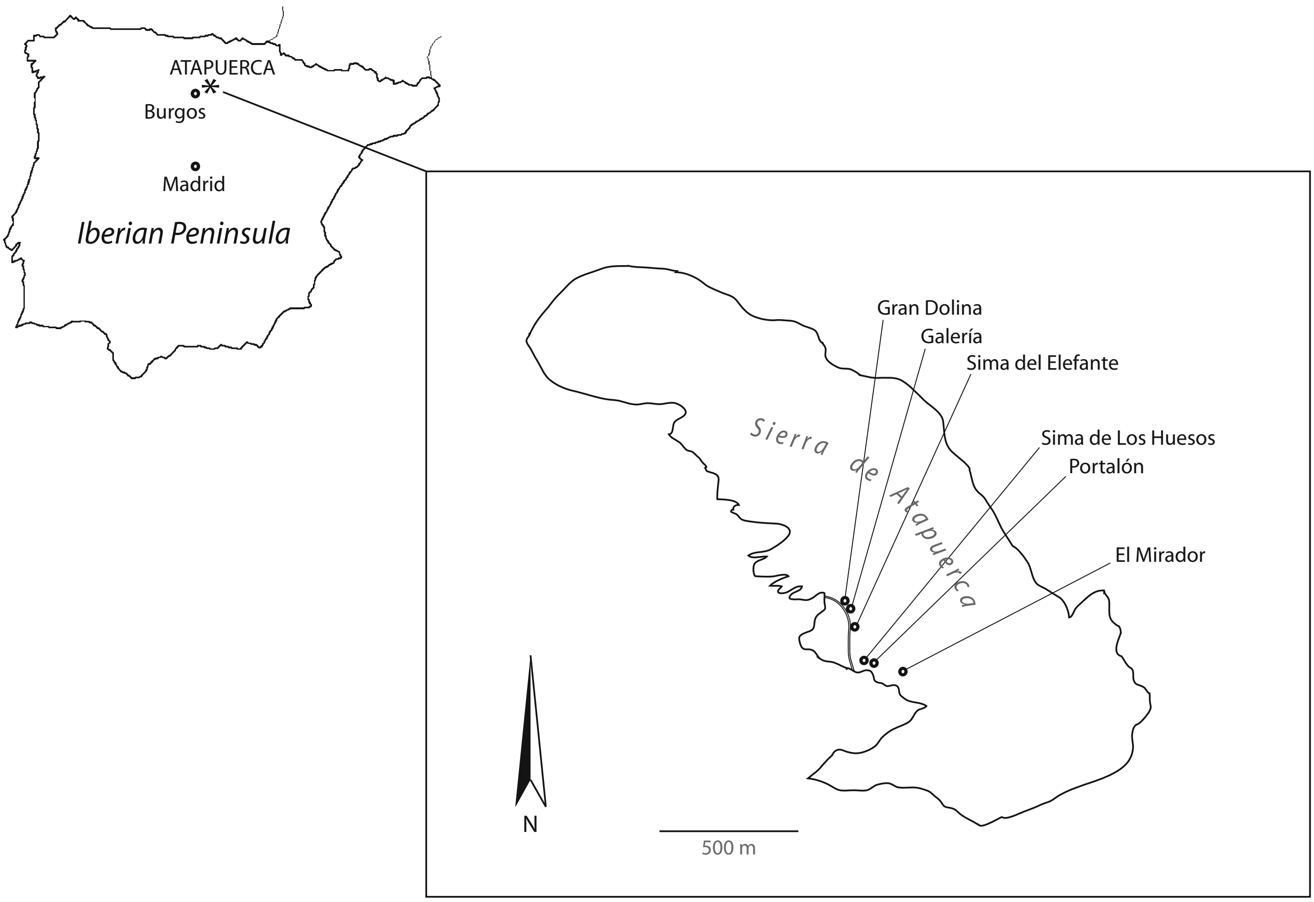
Atapuerca, or Sierra de Atapuerca, is a rich archaeological and paleontological site complex located 12 km east of the city of Burgos, in north central Spain (Figure 1). The sites consist of deeply stratified Lower Pleistocene to Holocene archaeo-sedimentary infills of different karstic caves and conduits within a Mesozoic limestone anticline at the boundary between the Tertiary basins of the Duero and Ebro rivers. Among the key sites, Gran Dolina, Galería, and Sima del Elefante (the railway trench sites) have yielded remains of Lower and early Middle Paleolithic occupations by different hominin species (Carbonell et al., 1999; Rosas et al., 2001; Carbonell et al., 2008). Sima de Los Huesos, a small, paleontologically rich gallery at the end of a 14-m deep sinkhole, has yielded a rich accumulation of hominin skeletal remains (Arsuaga et al., 1991, 1993, 1997, 1999). While the bulk of the Atapuerca sites span the Lower and Middle Pleistocene, two sites, El Mirador and Portalón, include Holocene deposits: Neolithic and Bronze Age remains have been explored in El Mirador (Vergès et al., 2002; Cáceres et al., 2007; Cabanes et al., 2009), and occupations from Upper Paleolithic to the Middle Ages have been found in Portalón (Carretero et al., 2008; Ortega et al., 2008).

All of the deposits are characteristic of cave entrance settings and consist of mixed quartz sand and sandy aggregates from nearby soils, red clay originating within the local karstic system, and limestone rubble from the immediate surroundings. The stratified sequences from the different sites each record a succession of high and low energy modes of gravitational deposition, including debris flows, runoff, and roof spall facies, as well as exokarstic stratified and microstratified waterlain deposits (Vallverdú 1999, 2001; Pérez-González et al., 2001; Mallol and Carbonell, 2008). None of the depositional sequences are continuous, and stratigraphic unconformities are frequent. The Holocene deposits from Portalón and El Mirador are primarily anthropogenic.

Postdepositional carbonate and phosphate diagenesis is prominent throughout the Pleistocene deposits. Overall preservation of bone is good, the smaller-than-2 cm fraction being most affected by diagenetic breakdown linked to decalcification. The Atapuerca flint comprises two geological types – one Neogene and the other Cretaceous in age. The former is highly susceptible to diagenesis due to its elevated percentage of moganite (a polymorph of quartz), and recovered artifacts made with this flint type are often found in poor states of preservation.

The Gran Dolina-TD6 deposit shows pedogenic evidence of calcareous brown soils suggestive of an Atlantic climate and sharp facies changes indicative of strong climatic fluctuations (Vallverdú et al., 2001). In contrast, the rest of the Gran Dolina and Galería deposits are weakly decalcified and bioturbated indicating a mixed Mediterranean/continental temperate climate (Pérez-González et al., 2001).

In-situ human occupation floors have been documented at Galería in layers GII and GIII, as well as in Gran Dolina layers TD10 and TD6, the latter in association with cut-marked human remains. No evidence of anthropogenic fire has been identified in any of the Pleistocene deposits. The Holocene sites, Mirador and Portalón, have yielded well-preserved combustion features and ashy




**Atapuerca, Figure 1** Location of Sierra de Atapuerca and the main archaeological sites mentioned in the text. The curved line adjacent to the sites represents a railway trench that exposed the archaeological deposits.

anthropogenic deposits. Rich stabling deposits and human burials dating to the Bronze Age have also been documented at Mirador (Cáceres et al., 2007; Angelucci et al., 2009; Carrancho et al., 2009).

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## Cross-references

Cave Settings
Chemical Alteration
Lithics
Paleoenvironmental Reconstruction
Site Formation Processes